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Hydrological characteristics as a determinant of sediment delivery in watersheds

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Abstract Coon Creek, Sand Creek, and similar stream systems in southwestern Wisconsin, USA, exhibit marked discontinuities in their channel networks and sediment budgets. The hydrological processes in these systems also demonstrate a variable response with scale. Groundwater-influenced reaches along the perennial parts of the stream respond to short duration summer storms. During the winter, groundwater levels in the tributary basins rise, enabling tributary channels to respond to snowmelt events. In Sand Creek, the stream system responded in an integrated manner only during a low magnitude (<l year R.I.) storm that occurred during the end of the snowmelt period.

Les caractéristiques hydrologiques, déterminante des apports de sédiments

Résumé Les réseaux hydrographiques et les bilans de sédiments de Coon Creek, Sand Creek, et des systèmes de rivières analogues dans le sud ouest du Wisconsin, USA, présentent des discontinuités bien marquées. Les processus hydrologiques de ces systèmes répondent aussi en d'une façon variable, suivant l'échelle considérée. Le bief de la rivière à écoulement permanent qui est influencé par les eaux souterraines, réagit aux orages brefs de l'été. En hiver, le niveau piézométrique des eaux souterraines dans les bassins versants affluents s'élève. Ceci permet aux cours d'eau tributaires de répondre aux épisodes de la fonte nivale. Dans le Sand Creek, le réseau de la rivière a réagi dans sa totalité, seulement pendant une averse de hauteur modérée à la fin de la période de la fonte nivale.

STATEMENT OF THE PROBLEM

A sediment budget allows comparison of the magnitude and rates of various erosion processes within a given system. The sediment budget that Trimble (1983) constructed for Coon Creek, Wisconsin, illustrates a distinctive pattern of sediment erosion and deposition. Most of the sediment eroded from hillslopes is not conveyed to stream channels and much of the sediment yield of the large streams is derived by bank erosion of stored sediment. Sediment transport and deposition processes do not operate in the absence of hydrological processes. The purpose of this paper is to investigate the hydrological controls that produce and maintain a discontinuous sediment delivery system.

In Coon Creek, there are several indications of these discontinuities in the sediment and hydrologic process. There is a significant reduction in sediment delivery ratios with increasing watershed area (Fig. 1). A close examination of the sediment yield data also indicates that the data are discontinuous and can be separated into hillslope source tributaries and valley channels. The distribution of alluvial fans in the drainage basin also indicates that many of the tributaries are not part of a continuous stream network (Fig. 1). The discontinuous nature of the drainage basin also can be illustrated by the percentage of tributaries that fail to enter into the next higher order tributary. This is particularly pronounced when low order tributaries meet significantly higher order streams with wide flat flood plains or adjacent terraces (Fig. 2).

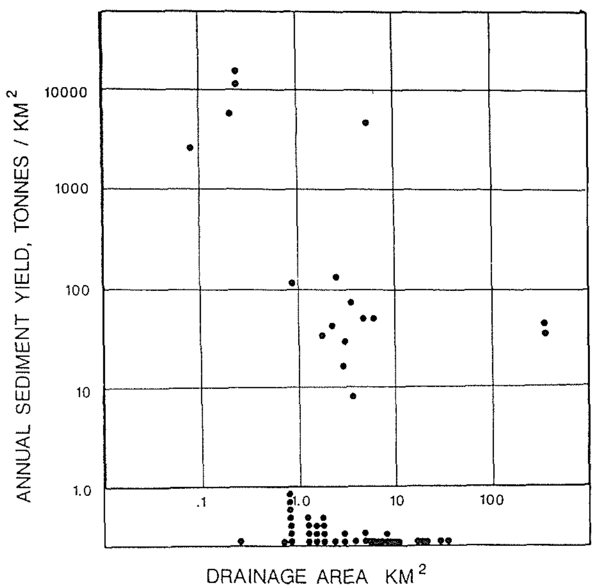

Fig. 1 Sediment delivery ratios, expressed as annual sediment yield (t km^{-2}), Coon Creek, Wisconsin. Dots at the base of the diagram indicate the drainage area of subwatersheds terminating in alluvial fans without joining the main stream channel.

In our estimation, discontinuous sediment delivery and stream networks imply discontinuities in streamflow and perhaps streamflow generation processes. Therefore, we will primarily be describing changes in the response

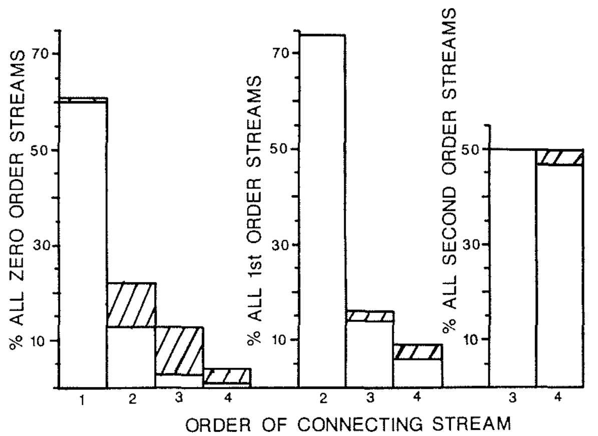

Fig. 2 Drainage linkages, Cook Creek, Wisconsin. Percentage of all zero order channels draining into streams of orders 1–4, etc. Shaded areas represent discontinuous connecting channels. Zero order streams are defined as topographic convergences not shown as streams on maps, but with known channels based on field evidence.

of different parts of the stream system to storm and snowmelt events.

STUDY SITE AND METHODS

Southwestern Wisconsin, USA, is a region of dissected ridge and valley topography. Hillslopes are steep, forested, and 150 to 200 m in relief. The wide flat valleys and ridgetops are used for agriculture. The region is underlain primarily by sandstone with a limestone cap in some regions. Coon Creek has a long record of sediment data, but this was not studied because of its large size and the difficulty of obtaining synoptic hydrologic data. The discontinuities exhibited by the sediment budget and stream network in Coon Creek are common to many streams in the region. We chose to study Sand Creek, a tributary to the Kickapoo River, which is one of the region's major streams. Sand Creek drainage basin is a representative basin in this region. It has discontinuous tributary channels in its downstream reaches, where the main valley is wide and the tributary channels are incised while the main channels are not. The stream sites are easily accessible so that the basin can be closely monitored during rainstorm and snowmelt events.

A network of 11 stream gauges has been installed in the basin (Fig. 3). Four of these gauges are automatically recording, and these monitor the perennial part of the stream system. Four raingauges are located along the length of the watershed. These are read during storm events and daily by a local resident. A recording raingauge was installed near the basin centre after the first year of data collection. An additional recording raingauge is located in an adjacent basin.

Stream sediment includes silt and clay transported in suspension and sand

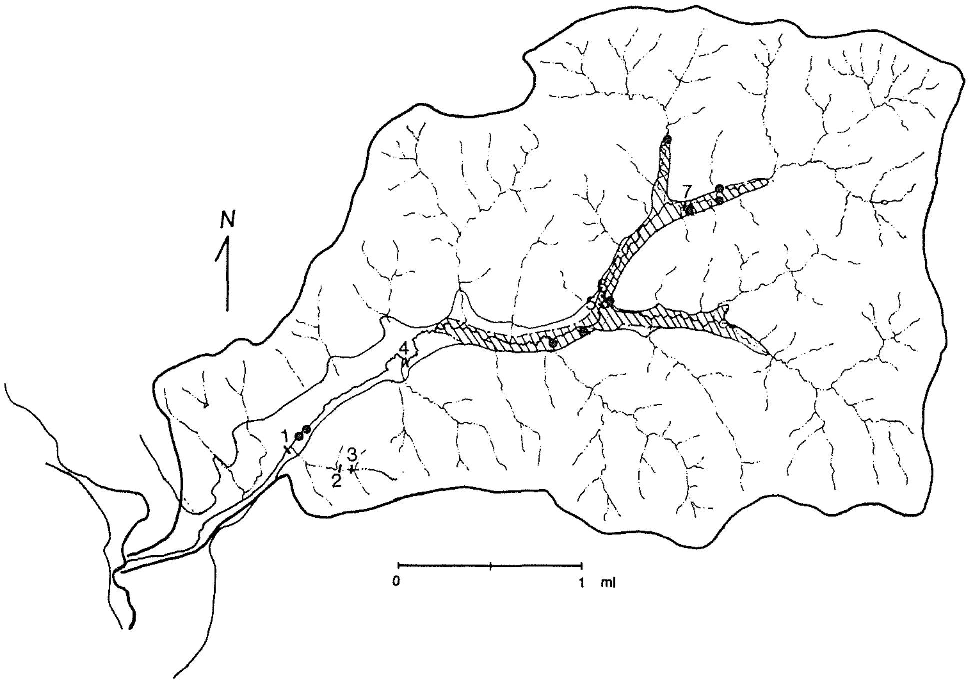

Fig. 3 Sand Creek drainage basin, Wisconsin. Numbers indicate the location of streamgauges and measured cross sections. Shaded areas are sites of erosion studies. The dark line surrounding the main stream channel marks the limit of the flat valley floor; the cross-hatched region marks areas of wetland vegetation; springs are marked by circles.

and gravel transported as bed load. Suspended sediment was monitored at gauging station sites during storm and snowmelt events. Erosion rates were monitored by surveying cross sections to determine bank erosion rates and by monitoring other sites with erosion pins.

The preliminary results of the study are reported below starting with the hydrologic process and their relationship to the erosion processes.

SEASONAL HYDROLOGICAL RESPONSE

Many rainfall-runoff models assume that the hydrological response will be similar throughout the drainage basin. We found that the drainage basin exhibited significantly different responses with watershed scale and that these responses varied with season.

Two hydrologically distinct events occur in the region: summer thunderstorm events and snowmelt events. We recorded 22 summer thunderstorms with total rainfall values ranging from 2 to 30 mm and averaging 30 minutes in duration. Most of these storms have a recurrence interval of less than 1 year, two events had larger recurrence intervals of 1.4 and 7 years (Hershfield, 1961). The stream response to these events was very minor; the soils were able to infiltrate most of the rain without producing runoff. Minor hydrograph rises were measured with the recording stream gauges. The response time of these storm events is variable, but is often rapid compared with other humid temperate regions of this size (Dunne & Leopold, 1978). A plot of hydrograph lag *vs.* drainage area illustrates the nature of the data from the automatically recording gauges; multiple storms were measured at each of the four stations (Fig. 4). Note that upstream of the spring-fed sources of the stream, no flow occurred in the channel. The hydrograph response time at each site is not constant, but varies with the storm events.

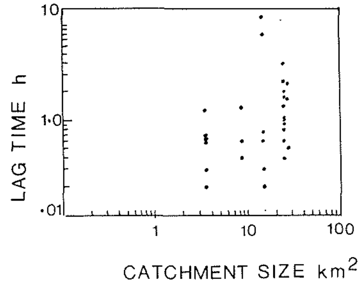

Fig. 4 *Hydrograph lag time (h) vs. drainage area (km^2), Sand Creek, Wisconsin. Results from 22 storms are shown.*

The main source of streamflow for the main channels is probably related to groundwater flow. This can be argued from the evidence that the main channel responded to the storm event in the absence of tributary flow and overland flow in the downstream parts of the basin. The overall groundwater discharge to the sites is created by the flow through the Ordovician St Peters sandstone underlying most of the region. The water table is near the surface along most of the Sand Creek valley. This is marked by the presence of sedges and other wetland vegetation along the channel (Fig. 3). Sand Creek is somewhat different from many of the larger channels, in that the entire valley of the main Kickapoo River is essentially a flood plain with the water table at the ground surface. Base flow in Sand Creek is highest near the spring source in the upper parts of the tributary. Springs also occur within the channel along the length of Sand Creek, but there are fewer sources downstream. This feature is also evidenced in the runoff rate *vs.* drainage area relationship for the storm events (Fig. 5). The four dots on this diagram cover the entire range of the summer storms shown on the previous diagram. This decrease in runoff rate with increasing catchment area during the base flow period is the opposite of what is seen in the regional analysis where baseflow in discharge per unit area is seen to increase with increasing drainage area for the major streams (Fig. 6). This is consistent with the observation of larger valley width and groundwater source associated with the larger channels. In

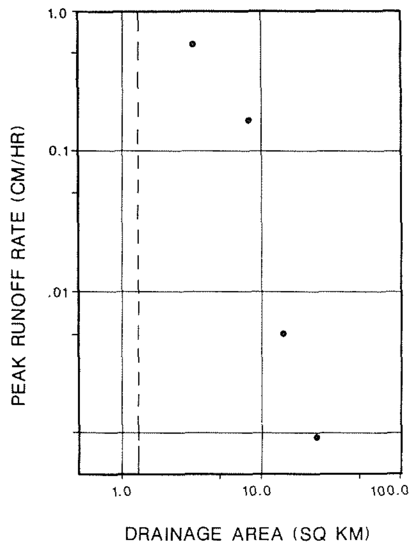

Fig. 5 Peak runoff rate (cm h^{-1}) vs. drainage area (km^2), Sand Creek, Wisconsin. Maximum of 22 summer thunderstorms.

Sand Creek, the primary groundwater source in addition to discrete springs is the marsh area along the stream channel.

Baseflow in the main channels is high even during dry summers, but it drops over the winter period. During the winter months, the piezometric surfaces rise in the tributary basins (Prestegaard & McHugh, unpublished). During the snowmelt period, 0.25 m of snow with a density of 0.45 g cc^{-1}, melted over a period of 10 days. In one small basin, both overland flow and rapid groundwater flow were generated during the snowmelt events. The combination of surface and subsurface flow, along with freeze-thaw activity, contributed to active gully erosion in the small basins. Runoff as overland flow was observed in the upper tributaries, but this flow infiltrated into the channel bed. Flow in the tributaries did not reach the recording gauge on the main channel. We recorded one rainstorm event during the end of the snowmelt period, when the groundwater table in the upper part of the basin was still high. This was the only event that caused integration of the drainage network, but was a similar magnitude event to the summer storm events.

One of our conclusions from this research is that groundwater maintains high baseflow in the main channels in this region, such as Coon Creek and the Kickapoo River. These large channels are surrounded by wide valleys with near surface groundwater that can respond rapidly during summer storm events. Therefore the main channels will create major flows during the summer, carrying with them sediment stored on the river floor, provided shear stresses are sufficiently high.

The tributaries, however, do not respond to the low recurrence interval storm events. The infiltration capacity of the soil is too high and the groundwater table is too low. During the winter period, groundwater levels in the tributary basins rise, due to the maintenance of the infiltration capacity of

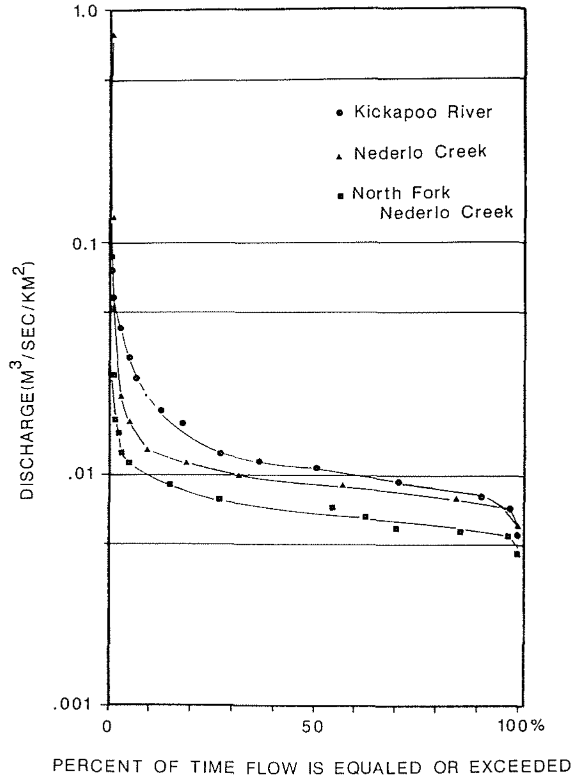

Fig. 6 Flow duration curves for three drainage basins in southwest Wisconsin, Nederlo Creek (14.5 km^2), North Fork Nederlo Creek (3.6 km^2), and the Kickapoo River basin (1595 km^2). Flow duration is normalized as m^3 s^{-1} km^{-2}. Curves are based on 10 years of daily maximum discharge data.

the soil upon freezing and the low evapotranspiration requirements during the winter period (Prestegaard & McHugh, 1988). Channel maintenance events occur separately in the two parts of the system. The discontinuities in channels occur between the dominance of groundwater flow and the base and surface-groundwater flow interactions in the tributaries.

EROSION SOURCES

One positive aspect of studying a stream system during periods of moderate to low flow is that erosion events can be isolated from runoff events. In a region with intense freeze-thaw activity, such as southwestern Wisconsin, one can evaluate the importance of transport of material by such processes in the absence of major flow events. During the 1987-1988 period, stream channel cross sections eroded, but more obvious was the fresh erosion along the steep channels of the tributaries. These tributaries were filled with snow during the winter and lost sediment from hillslopes and channel banks during snowmelt and freeze-thaw events.

Moderate magnitude snowmelt and summer storm events produce hydrologic responses in different parts of the channel network. Sediment is continuously prepared every winter by freeze-thaw activity, but is often not transported out of the channels. In 1978, the region was affected by a large magnitude summer storm (R.I. approx. 100 years). This event, like the spring storm, affected all parts of the channel. It was capable of cleaning silt out of the stream and depositing gravel bars under bridges and at other sites, and scouring the streambed to the sand or bedrock floor. Since that time, the stream has been filling with fine sediment, most of it derived from the channel banks. Much of the tributary sediment is redeposited before it reaches the main channel.

CONCLUSIONS

In Sand Creek, a change in the hydrological behaviour of the system occurs at the junction between the small tributaries with low groundwater tables and the larger channels with near surface groundwater. Most gauging stations in Wisconsin and throughout much of the world are located on large perennial channels, and therefore are not capable of monitoring these changes in hydrological behaviour that can have such a profound influence on erosion and deposition processes in the drainage basins.

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