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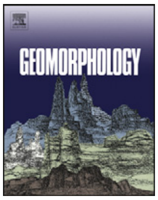

Upland sediment supply and its relation to watershed sediment delivery in the contemporary mid-Atlantic Piedmont (U.S.A.)

S.M.C. Smith [a,*], P.R. Wilcock [b]

[a] University of Maine, School of Earth and Climate Sciences, Bryand Global Science Center, Orono, ME 04473, USA
[b] Johns Hopkins University, Department of Geography and Environmental Engineering, 3400 North Charles Street, Ames Hall 313, Baltimore, MD 21218, USA

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ABSTRACT

We use sediment accumulation in ponds and reservoirs to examine upland sediment sources and sinks in the Piedmont physiographic region of Maryland, USA. In zero-order and first-order watersheds, sediment yield is greatest from suburban land cover, followed by agriculture and forest. The idea that sediment yield is small from mature suburban development appears to not be correct. First-order channel enlargement is an important sediment source, causing sediment yield to increase from zero-order to first-order watersheds. Nonchannel sources provide one-third to two-thirds of the upland sediment load.

Long-term sediment accumulation in a reservoir at fifth-order indicates that cumulative sediment load from upland areas is reduced by one-quarter by net valley bottom sedimentation. If upland supply exceeds the load delivered from a watershed, sediment must accumulate along valley bottoms. In our study watershed, net sedimentation rate (sedimentation less erosion) averaged over valley bottom area is 2.6 mm/y, a value that is similar to independent direct measurements of sedimentation and erosion in a nearby watershed. Evaluation of the relative contributions to sediment mass balance of upland supply, valley bottom sedimentation and erosion, and watershed delivery indicates that, if valley-bottom rates of sedimentation exceed erosion as indicated by recent studies, then the proportion of watershed sediment delivery derived from stream banks is necessarily small.

Although sediment yield estimated from stream gage records is similar in magnitude to that from ponds for watersheds smaller than 20 km^2, sediment yield from reservoir sedimentation is a factor of five larger than that estimated from gage records for watersheds larger than 140 km^2. This observation confirms that the different methods provide very different estimates of sediment yield. This possibility is reinforced by a sediment yield of 14 Mg/km^2/y from a gage immediately above a reservoir with a yield of 142 Mg/km^2/y based on reservoir accumulation.

1. Introduction

The mechanisms and rates associated with sediment erosion, transport, and storage change with increasing spatial scale. As water flow and sediment move from relatively steep upland hillslopes and channels to lower gradient alluvial valleys, the balance between upland sediment production and sediment yield over a decadal time scale is mediated by deposition along lowland channels and floodplains, typically producing yield that is smaller than upland supply. This has been termed the sediment delivery problem and is often approximated using a sediment delivery ratio that expresses the sediment delivered to a point in a watershed as a proportion of the amount of sediment eroded upstream (Walling, 1983; de Vente et al., 2007). The magnitude of the ratio generally decreases with drainage area but specific values and their variation with basin size depend on many factors. A wide range of sediment delivery factors are reported in the literature (Roehl, 1962; USDA, 1983; Scatena, 1987; Kinnell, 2004; Walling and Horowitz, 2005).

A predictive understanding of sediment delivery is of pressing importance because excess sediment and related turbidity are widespread impairments in rivers and coastal waters. Expenditures required to reduce sediment loading to specific goals will be enormous, and it can be difficult to demonstrate that any particular investment will achieve the desired result. Remediation and restoration actions may reduce sediment loading at specific locations, and some basis is needed for estimating the proportion of that reduction in sediment supply that appears farther down the watershed. A sound approach requires evaluation of landscape position and the magnitude of individual sediment sources. Information to guide this work is available primarily at the scale of hillslope plots or larger rivers on which gages exist (Table 1). Much less is known about sediment sources and sinks in the upland watersheds between plot scale and higher order rivers (Strahler,

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[*] Corresponding author. Tel.: +1 207 581 2198.
E-mail addresses: sean.m.smith@maine.edu (S.M.C. Smith), wilcock@jhu.edu (P.R. Wilcock).

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Table 1
Sediment yield estimates from previous studies.

DA km^2	SY Mg/km^2/y	Location description	Reference
11	812	L. Falls	Wark and Keller (1963)
123	648	NW Br	"
150	98	Difficult Run	"
161	560	Rock Cr	"
173	16	Catoctin Cr	"
262	112	Seneca Cr	"
381	51	Bull Run	"
728	68	Antietam Cr	"
1280	76	Conococheague Cr	"
0.01	49,037	Downstream from active urban construction	Wolman and Schick (1967)
0.08	28,021	"	"
0.24	8406	"	"
0.24	3958	"	"
0.61	25,219	"	"
1.74	402	"	"
2.15	1961	"	"
11	813	"	"
25	11,384	"	"
128	648	"	"
161	560	"	"
189	371	"	"
	8743	Urban construction	Guy and Ferguson (1962)
	22,417	Highway construction	Vice et al. (1969)
	572	Average cropland yield from three basins <5 km^2	Yorke and Herb (1978)
	818	Urban yield with min. construction	"
	22; 442	Forest — min; max. Eastern region estimate	Patric et al. (1984)
	31	Forest — mean Eastern region estimate	"
	9	Forest — West VA headwater SY	"
	17	Forest — mean SY from small watersheds	"
	0.67; 72	Forest — min.; max plot study SY	"
	56	Forest — recommended SY for minimal disturbance	"
	6324	Anacostia River W'shd — quarry	Scatena (1987)
	124	Anacostia River W'shd — stream	"
	4954	Anacostia River W'shd — construction	"
	184	Anacostia River W'shd — agriculture	"
	24	Anacostia River W'shd — urban	"
	9	Anacostia River W'shd — forest	"
	400	Anacostia River Watershed — total	"
	68	Baltimore County Farm — gaged Ag	"
	123; 245	Baltimore County Farm — deposits	"

1957; Boomer et al., 2008; Smith et al., 2008a, 2011). This paper contributes to resolving this problem by presenting sediment yield observations at the scale of first order basins and comparing these values of sediment supply to sedimentation rates in a reservoir at fifth order.

Because the relation between sediment transport rate and water flow is nonlinear and subject to nonstationarity from a number of factors, values of sediment yield can be difficult to estimate from gaging observations collected over short time intervals. Long-term sediment delivery rates can be reliably estimated from sediment accumulation in ponds and reservoirs, and further use of this valuable information source would greatly benefit evaluation of watershed sediment budgets (STAC, 2013). A common challenge with pond and reservoir sediment accumulation observations is that the mix of land uses in the contributing watershed often changes, making it difficult to assess the effect of any particular land use on sediment supply. Here, we use observations of sediment accumulation over decadal and longer periods in six ponds draining zero- and first-order watersheds to document sediment yield from upland watersheds. Land cover in the study basins varied little during the period of sediment accumulation; and land cover in each basin was predominantly agricultural, forest, or suburban, the three dominant land-cover types in the contemporary upland landscape of the mid-Atlantic Piedmont.

The upland basins are located in central Maryland and vary in size from 0.08 to 0.69 km^2 (Fig. 1). The objective of the measurements was to estimate sediment yield associated with each land cover in order to provide a basis to cumulate upland sediment yield across a larger watershed. We compare the cumulated upland supply to sediment storage in a reservoir on a fifth-order stream to assess the extent of sediment storage along the channel network. Three of the six ponds drain to this reservoir, and the remaining three are nearby in similar physiographic settings (Reger and Cleaves, 2008). Comparison of sediment delivery to first- and fifth-order channels supports a discussion of contemporary rates of upland sediment supply and the effect of spatial scale on sediment delivery.

2. Sediment yield in the mid-Atlantic Piedmont

The Piedmont is a dissected landscape with a thick mantle of regolith overlying schist and quartzite bedrock in most areas (Pavich, 1989). Both chemical solution and mechanical erosion have been shown to play an important role in regional denudation (Cleaves et al., 1970, 1974; Wolman, 1987). Smith (2011) reported that approximately two-thirds of the Piedmont landscape is comprised of first-order basins ranging from 0.11 to 1.40 km^2 that contain the external links of the watershed channel networks. The upper termini of the channels within first order basins typically receive inflow from nonchanneled upland valleys, herein referred to as zero-order basins that receive drainage from surrounding hillslopes. Most of the remaining watershed areas consist of nonchanneled hillslopes and zero-order basins that drain directly into channels of second or higher order.

The first-order basins are characterized by valley profiles that are the steepest components of Piedmont valley networks. Upland valleys in the typical dissected Piedmont are relatively confined and typically show little evidence of alluvial deposition in the form of overbank deposits in the riparian corridor. Sediment can be stored as colluvial deposits in upland valleys for decades to centuries (Costa, 1975). Although first-order stream channels show little evidence of alluvial deposition, erosion from channel extension, incision, and widening can augment upland sediment supply (Allmendinger et al., 2007).

Persistent alluvial storage deposits commonly appear along second-order streams, and floodplain storage becomes extensive farther downstream in broader, lower gradient valleys (Happ, 1945; Costa, 1975; Trimble, 1977; Jacobson and Coleman, 1986; Pizzuto, 1987; Pizzuto and O'Neal, 2009; Schenk and Hupp, 2009). Alluvium, often more than a meter thick, covers the lowland valley bottoms. Much of the deposition is a legacy of intensive deforestation and agricultural erosion in the nineteenth and early twentieth centuries (Costa, 1975; Jacobson and Coleman, 1986). Happ (1945) notably drew attention to the burial of pre-colonial valley surfaces by modern agricultural age sediment in southern Piedmont streams and observed that higher sedimentation rates can occur in valleys inundated by man-made impoundments. Walter and Merritts (2008) have shown that eighteenth and nineteenth century dams have played an important role augmenting valley bottom sedimentation. Observations in suburban Maryland show that valley sedimentation has continued in contemporary Piedmont valleys in an urbanizing setting (Leopold et al., 2005).

Previous watershed sediment budgets developed for Maryland's Piedmont have involved estimates of upland sediment supply. Costa (1975) calculated the supply from published observations of soil erosion at the field scale and estimated sediment storage as the difference between that value and watershed sediment yield derived from reservoir sedimentation. Allmendinger et al. (2007) estimated first-order basin sediment yield from land-cover based upland supply and field evaluation of channel enlargement. Jacobson and Coleman (1986) and USEPA (2009) relied on application of the Universal Soil Loss Equation (USLE).

Although the link between upland sediment sources and sediment yield is addressed in many of these studies, direct evidence of the