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

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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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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

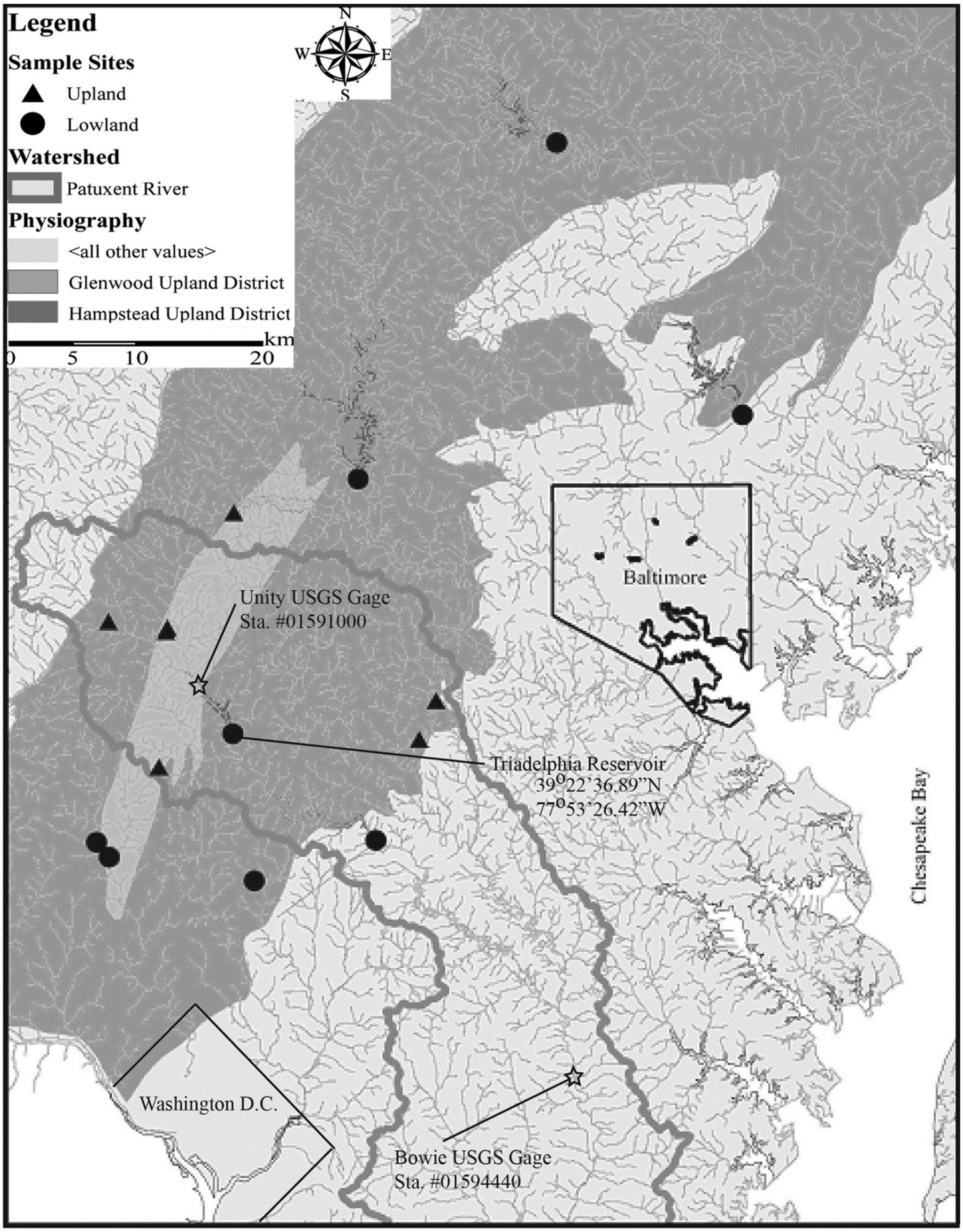

Fig. 1. Study area showing the HUD and GUD subareas of Maryland's Piedmont Plateau physiographic province (Reger and Cleaves, 2008). The Patuxent River watershed is shown by the dark gray line. The UPRW extends downstream to the Triadelphia Reservoir as shown in the map.

sediment production and storage in first-order watersheds is limited. In addition, the methods previously used are subject to considerable error that can be difficult to constrain. Because sediment delivery can be either augmented by erosion or diminished by deposition and because patterns of these changes should be controlled by the topographic configuration of the channel network and valley bottom, reliable measurements of upland sediment yield are of particular importance in understanding and managing sediment sources. The sediment yield from zero- and first-order watersheds reported here adds useful information to future sediment budgets.

The mid-Atlantic Piedmont has been a location of focused concern regarding sediment yield because sediment is identified as one of the important pollutants contributing to decline in water quality in Chesapeake Bay. Erosion of river banks has been invoked as a sediment source mechanism in modern watersheds along the East Coast of the United States (Wolman, 1959; Meade and Trimble, 1974; Langland and Cronin, 2003; Fraley et al., 2009). The common occurrence of tall banks associated with incised gullies and thick alluvial deposits within alluvial valleys raises the question of whether hillslopes or streams are the dominant contemporary source of fine sediment to the Bay. Large sediment loads have been calculated from suspended sediment transport samples in the larger rivers draining the Piedmont (Gellis et al., 2004). Land cover changes have altered storm and presumably contributed to increased loadings, particularly during periods of intense urbanization in some locations over the past 70 y (Wolman, 1967). An important motivation for investigating sediment yield in the Maryland Piedmont is to contribute reliable sediment yield information to support sediment management in the Chesapeake Bay watershed.

3. Sedimentation rates in ponds and reservoirs

Pond and reservoir sedimentation integrates sediment yield over time, potentially providing a tool to address the temporal limitations and estimation challenges of short-term storm sampling in many locations (Walling and Webb, 1981). This data source could be used more extensively to evaluate sediment yield across basin scales (Bogena and Diekkruger, 2002; Smith et al., 2002). Techniques for measurement of impoundment sedimentation and the development of relations between accumulated volumes and watershed yield have been described by Barnes and Brown (1939), Gottschalk (1945), Chow (1964), Vanoni (1975), and Verstraeten and Poesen (2002). Recognition of the importance of this data source has led to development of databases for use in estimating sediment yield (Gray et al., 2010).

The six small basins discussed here contain ponds with drainage areas ranging from 0.08 to 0.69 km^2 (Table 2). The dominant land cover is forest for two ponds and row crops for two ponds, with the last two draining suburban areas developed from agricultural land after 1970. Continuity of land cover within each basin over decadal time scales was confirmed using historic aerial photographs obtained from the Maryland Department of Natural Resources and Howard County Soil Conservation District (HCSCD).

All of the study basins are dominated by a crystalline bedrock lithology, located within the Hampstead (HUD) and Glenwood (GUD) Uplands physiographic districts of the Maryland Piedmont (Cleaves et al., 1968; Reger and Cleaves, 2008) (Fig. 1). The two districts are similar; however, the GUD has slightly less relief and dissection. Soils in each district are dominated by loamy textures in the uplands and slightly finer grained silt loams in the lowland alluvial valleys (USDA, 2008).

Each of the ponds in the six basins had an operational lifespan of at least 10 y and is still in existence today (Table 2; Fig. 2). Pool area <0.02 km^2, and pool depth <5 m in all cases. Sediment trap efficiency was estimated for each pond using the method of Brune (1953) supported by pond bathymetry measurements, watershed delineations based on 1.52-m topographic elevation contour information (HOCO, 1994), and water balance information summarized for the area by MGS (1995). The efficiency estimates exceed 85% for all of the structures.

Several lines of evidence were used to determine the sediment accumulation thickness in each pond, including (i) guidance on pond construction protocols, including pool excavation depths, from HCSCD staff; (ii) pool depths specified by pond design plans; (iii) a bathymetric survey of each pond; (iv) documentation of the sediment volume extracted for pond maintenance at each pond provided by local government agencies; and (v) stratigraphic evidence from cores of the pond sediment. Where possible, field surveys were supplemented with discussions with local government staff or land owners to verify the design and management history of the ponds.

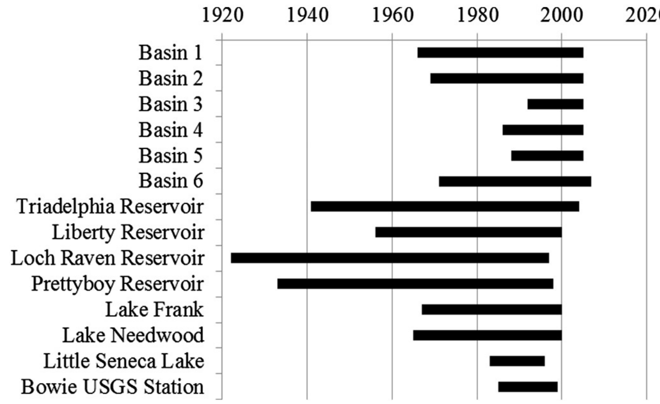

Fig. 2. Approximate time span of sedimentation measured in the ponds and reservoirs used to estimate sediment yield.

Five cores were extracted from each impoundment, with the exception of basin 6 in which sediment storage was directly determined from pond excavations supervised by a local government agency. Prior to coring, the configuration of each deposit was mapped in order to define zones with different hydraulic and depositional characteristics (Fig. 3). The ponds were relatively small, allowing us to assess depositional patterns and complexity. We also retrieved a high density of depth measurements in each pond. The field observations, depth measurements, and design information from local government agency staff were used to delineate the pond zones and identify locations for the core extractions. Zone 1 is the pond delta area, zone 2 is the middle of the pond in the location of the preexisting stream channel, zone 3 is the downstream end of the pond near the outlet riser structure (generally with the longest flow path), and zone 4 includes marginal areas on either side of zone 2 that typically form a bench from which dam construction materials were excavated.

Table 2
Study areas identified in Fig. 1; physiographic setting based on map by Reger and Cleaves (2008);
F = forest, A = agriculture, Mw = meadow, S = suburban, C = construction, Mx = mixed; subdominant land cover indicated by parentheses.

Study site	Physiographic setting	DA (km^2)	Dominant land use	Stream order	Lifespan (y)	SY Mg/km^2/y
Upland						
Basin 1	Hampstead Upland	0.28	F (A)	1	39	144
Basin 2	Glenwood Upland	0.08	F (Mw)	1	36	33
Basin 3	Glenwood Upland	0.17	A	1	13	336
Basin 4	Glenwood Upland	0.28	A	0	19	103
Basin 5	Hampstead Upland	0.38	S	2	17	529
Basin 6	Glenwood Upland	0.69	S	2	36	371
Lowland						
Triadelphia Reservoir	Hampstead Upland	203	Mx	5	63	142
Liberty Reservoir	Hampstead Upland Patapsco Gorge	425	Mx	5	43	118
Loch Raven Reservoir	Chattolannee Upland Timonium Valley Gunpowder Falls Gorge	568	Mx	5	74	230
Prettyboy Reservoir	Hampstead Upland Gunpowder Gorge	207	Mx	5	65	321
Lake Frank	Glenwood Upland	33	Mx	3	33	148
Lake Needwood	Hampstead Upland	35	Mx	3	33	278
Little Seneca Lake	Hampstead Upland	56	Mx (C)	3	13	695

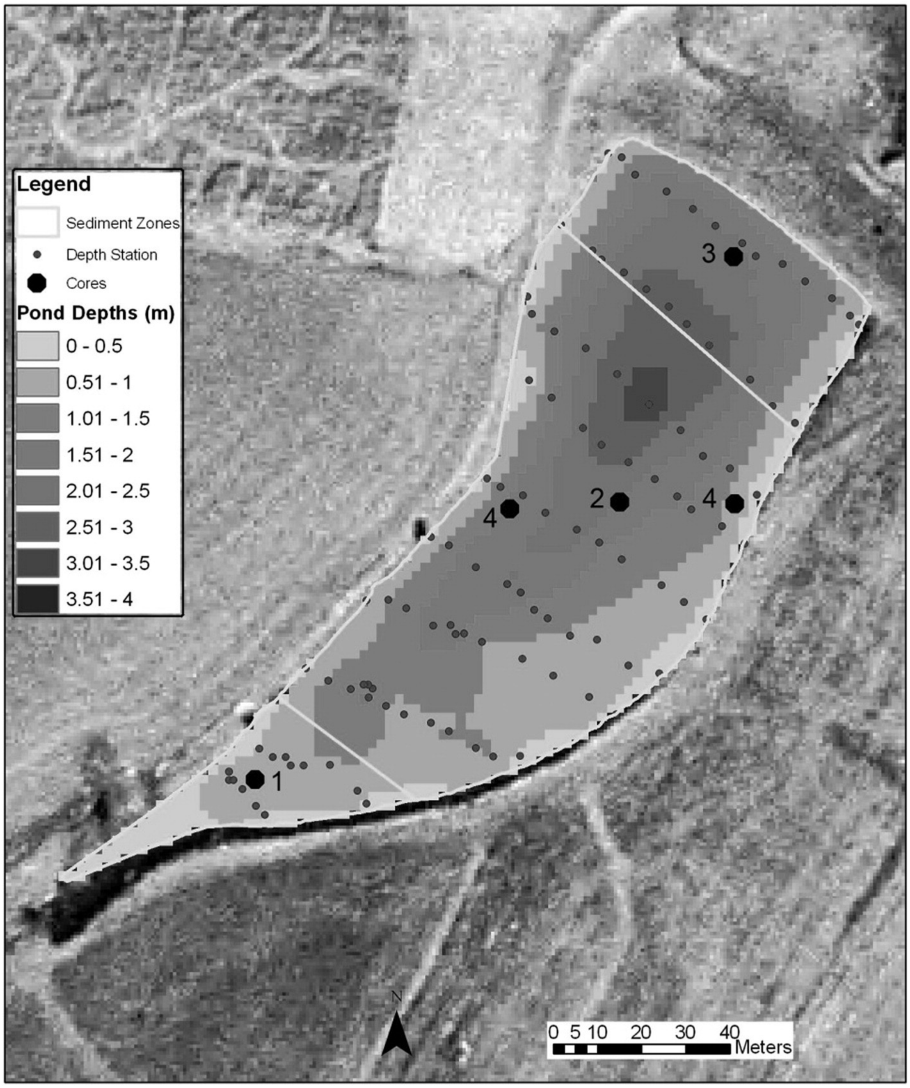

Fig. 3. Upland pond sediment sampling schematic. Numbers correspond to pond sediment accumulation zones described in the text.

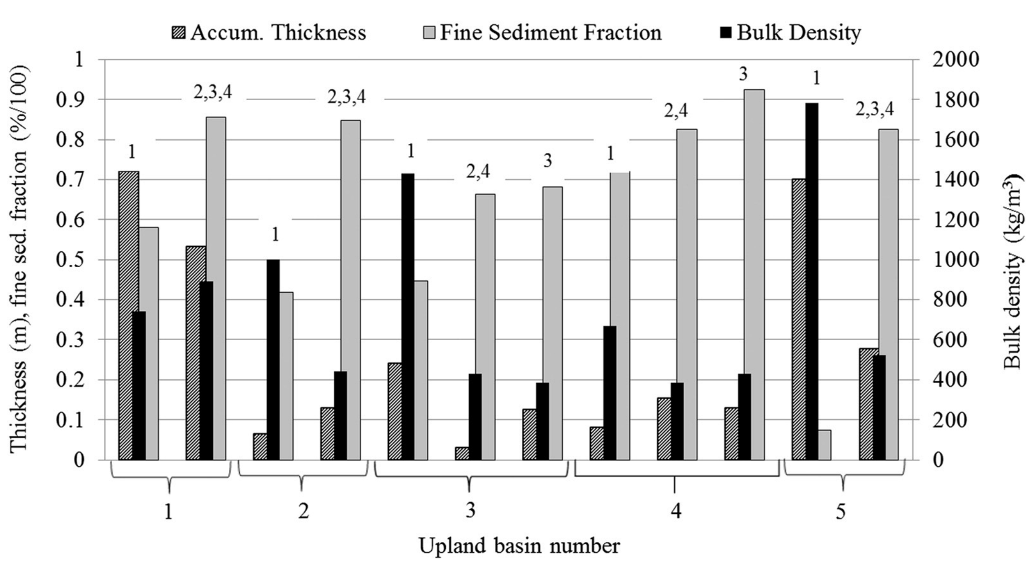

Fig. 4. Upland pond sediment characteristics. Labels denote sediment accumulation zones within each pond. Grouped labels represent values averaged from multiple zones.

Sediment cores were collected with an aluminum tube of length 3.05 m and diameter 0.08 m with a *core catcher* on the bottom end. A backpack vibra-coring apparatus was used with a steel tripod to guide the tube. The length of each core was determined based on the penetration depth allowed by the coring apparatus or depth of refusal. A minimum depth of 1 m was attempted in each core location. The length of the tube above the pond bottom was measured at maximum penetration depth. A second interior length measurement was made from the top of the core tube to the core sample. The two lengths provide a basis to estimate core compaction resulting from the core extraction process.

Stratigraphic units were delineated by changes in sediment texture and color and separately analyzed for grain size distribution and bulk density. Dry bulk density measurements were conducted on the subsamples using methods described by Park et al. (1999) and Bennett and Lambert (1971). Each subsample was weighed before and after drying, allowing for a determination of the percentage of water. Bulk density was then calculated for each subsample. Grain size was measured using standard procedures outlined by Poppe et al. (2000) to provide percent gravel, sand, silt, and clay in each core subsample. Core-weighted averages of the grain size and dry bulk density within the thickness of the sediment accumulation layer were calculated using the subsample values following the core shortening adjustment (Fig. 4).

Stratigraphic indicators of the original pond bottoms included changes in sediment grain size distribution, texture, color, dry bulk density, and water content. Increases in bulk density are particularly useful indicators because pond bottom areas are often compacted during construction. In contrast, sediments that have deposited in backwatered environments usually have lower bulk density and higher water content. Changes in grain size and laminations of organic materials and sediment also provided indicators of subaqueous deposition processes typical of backwater areas.

The accumulated sediment mass in each zone was calculated as the product of the surface area of each sedimentation zone, and thickness and bulk density of the accumulated sediment were determined from the core representative of the zone. Sediment yield was calculated as the sum of the mass deposited in each zone, adjusted for trap efficiency, and divided by the pond life and contributing drainage area.

Sediment in the clay and silt size classes (finer than 0.0625 mm) composed 63 to 84% of the accumulated mass in the sampled ponds (Fig. 4), with sand and gravel forming the balance of the sedimentation. This is a broader range of coarse sediment than observed by Yorke and Herb (1978), who found that sand composed <20% of sampled sediment transport in the region and estimated bedload by calculation using a transport function. Our sedimentation measurements provide a more certain estimate of coarse sediment yield as ponds are usually effective at trapping that portion of the load, but they may also undersample the wash load that can possibly pass through the outlet structures. Sedimentation was generally coarsest in the pond deltas at the upstream end of each pond. Basins 2 and 4 had relatively thin delta accumulations, and the delta in basin 4 was almost entirely fine-grained.

Sediment deposition was also measured in Triadelphia Reservoir, which was constructed on a fifth-order reach of the Patuxent River mainstem in 1943 (Fig. 1). The impoundment captures flows from the 203-km^2 Upper Patuxent River watershed (UPRW). Sounding measurements were taken to estimate the existing reservoir bottom elevation (Ortt et al., 2008a). The accumulated sediment volume is derived by comparing the present bottom to pre-dam valley topography estimated from pond construction information and the stratigraphic indicators derived from sediment cores. Mass of the sediment volume is calculated using bulk density measurements from cores extracted from the reservoir in 1998 (OSI, 1997). Ground-based topographic surveying was conducted in deltaic tributary confluence areas to include portions of the reservoir too shallow for boat access (Smith et al., 2008b). The sediment load from the upstream watershed was found using a trap efficiency of 95% (USEPA, 2009) and the lifespan of the impoundment.

We also make comparison to previous measurements of reservoir sedimentation in the Maryland Piedmont. The Prettyboy and Liberty Reservoir watersheds, located north of the UPRW, have similar land use history and were previously surveyed by Ortt et al. (2000, 2008b). Prettyboy Reservoir was constructed on the Gunpowder River in 1938 and Liberty Reservoir on the North Branch of the Patapsco River in 1956. Sedimentation was also measured by Ortt et al. (2000) in Loch Raven Reservoir, which is downstream of the Prettyboy Reservoir on the Gunpowder River. Sedimentation in Loch Raven Reservoir was previously used as a data source for a watershed sediment yield published by Costa (1975).

Sedimentation surveys are also reported for two intermediate-sized impoundments south of the UPRW by MNCPPC (2000). Lakes Frank and Needwood have drainage areas less than half that of the fifth-order watershed reservoirs. Both were constructed in the 1960s for sediment and flood control. An evaluation of sediment trapping efficiency in Lake Frank was conducted in 1980, concluding that the impoundment retained 96% of the sediment that it received (MNCPPC, 2000).

The sediment mass within each of the higher order watershed impoundments is calculated using available sediment volume and bulk density measurements. Core samples were not retrieved from Prettyboy and Liberty Reservoirs, so bulk density measured for Loch Raven Reservoir core samples was applied. Bulk density values applied to lakes Frank and Needwood were estimated as an average of the samples extracted from the upland ponds and Triadelphia Reservoir. Sediment yield for each impoundment watershed was calculated using measurements of sediment accumulation, bulk density, and the contributing watershed area.

4. Results

4.1. Upland watershed sediment yield

Sediment yield (SY) for the six ponds is presented in Fig. 5. The proportion of the yield estimated from first-order channel enlargement shown in the chart is estimated from several lines of evidence. Topographic surveys using field measurements and aerial photography were used to quantify channel erosion volumes in basins 1, 5, and 6 that were converted to mass based on soil bulk density information (USDA, 2008). Sediment yield values calculated for basins 3 and 4 were compared to estimate the channel erosion contribution in basin 3. The use of the comparison is based on the observation that basin 4 is adjacent and nearly identical except that a channel does not exist upstream of its receiving pond.

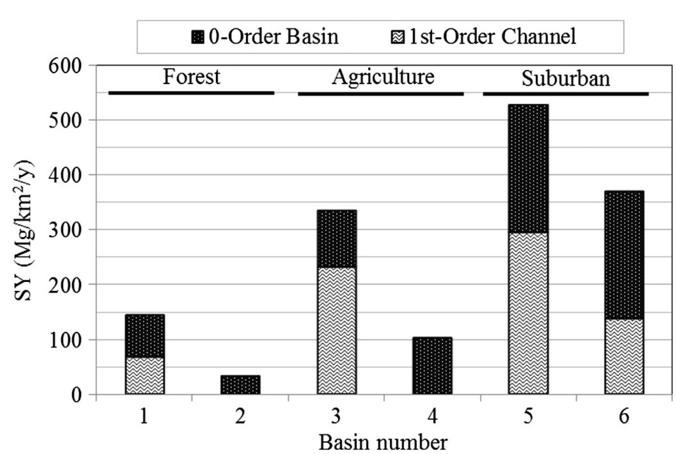

Fig. 5. Sediment yield from six ponds under different land cover conditions.

Of the two forested subwatersheds, SY in the smallest of the subwatersheds (basin 2) is 33 Mg/km^2/y. The result is similar to the mean value of 31 Mg/km^2/y for small forested basins derived by Patric et al. (1984) using 291 measurements of soil erosion, stream sediment transport, and reservoir accumulations in the eastern United States, many of which are presented in an earlier overview by Patric (1976). In contrast, the yield from basin 1, 144 Mg/km^2/y, is well over four times larger. Although the uppermost portion of basin 1 contains row crops, measurements of suspended sediment flux from agricultural and forested hillslopes in the basin indicate that the yield from nonchanneled forested areas was at least twice the yield measured in basin 2 (Smith, 2011). Localized erosion and surface transport were observed in confined overland flow pathways within the forested nonchanneled upland valleys of basin 1. In addition, the first-order channel in basin 1 is actively head-cutting, leaving a longer and larger channel. Comparison of suspended sediment flux in that channel and contributing zero-order basin indicates that nearly half of the SY in basin 1 (69 of 144 Mg/km^2/y) has been produced by channel enlargement, an estimate that is consistent with the dimensions of the existing channel compared to its likely dimensions when the pond was built approximately 40 y earlier. The measurement of a sediment yield that is larger than previous estimates for forested uplands is consistent with the observation of erosion by concentrated overland flow and first-order channel enlargement (Wark and Keller, 1963; Patric et al., 1984).

Sediment yield from ponds on agricultural land is 336 Mg/km^2/y for basin 3 and 103 Mg/km^2/y for basin 4. The basin 4 watershed is nonchanneled, whereas the watershed of basin 3 is drained by a first-order channel. Given that the two watersheds are adjacent and have the same soil and cropping history, the difference in SY may be attributed to the erosion of the channel in basin 3, a supposition supported by the presence of a relatively large, coarse delta in basin 3 and the absence of coarse sediment and a delta in basin 4. A value of 103 Mg/km^2/y applied to the nonchanneled portion of basin 3 represents a difference of 233 Mg/km^2/y, the magnitude of which corresponds to a sediment load generated by erosion of the channel in basin 3 that is consistent with its dimensions.

A sediment yield of 103 Mg/km^2/y from nonchanneled agricultural land is an order of magnitude smaller than the edge of field (EOF) yield of 1117 Mg/km^2/y estimated from USLE calculations for *no-till* cropland in Howard County, Maryland (NRCS, 2007). Scatena (1987) found that the USLE overpredicted loads by 45% in the adjacent Anacostia watershed. The large difference between our observations and USLE values may result, in part, from the presence of grassed waterways in both of the watersheds in this study. Well-maintained grassed waterways can reduce sediment yield by as much as 90% through swale stabilization and sediment trapping (Fiener and Auerswald, 2003; Gharabaghi et al., 2006).

Sediment yield to the two ponds draining suburban land are the largest observed, 529 Mg/km^2/y for basin 5 and 371 Mg/km^2/y for basin 6. Both of the watersheds have first-order channels upstream of the receiving ponds, and comparison of present conditions with historic photos and field observations indicate that the channels have enlarged since pond construction. Comparison of channel dimensions under present and pre-pond conditions estimated from historic aerial photos indicates that channel erosion has contributed the equivalent 295 Mg/km^2/y (55%) to basin 5, leaving 234 Mg/km^2/y for upland erosion. Although a pre-pond channel existed in basin 6, little information is available regarding its dimensions. Applying the basin 5 upland yield to basin 6, which is in the same suburban area and physiographic setting, leaves 137 Mg/km^2/y from channel enlargement. This corresponds to 48% of our estimated volume of the present basin 6 channel, a plausible volume of channel enlargement, providing a useful constraint on the upland versus channel contribution to basin 6.

A suburban upland supply of 234 Mg/km^2/y in basin 5 is larger than supplies observed in either forested or agricultural uplands. Both suburban watersheds were reported by local government agency staff to have been *built-out* when the ponds were constructed as permanent impoundments. The pond measurements indicate that a considerable sediment yield can continue after the period of initial construction and that this sediment is derived, at least in part, from sources other than channel enlargement. The observed persistence of substantial sediment loads from suburban land contradicts a common assumption that upland areas with mature development produce relatively little sediment upon the termination of construction (Wolman and Schick, 1967). Field observations during storms suggest that persistent localized disturbances from infrastructure maintenance, yard work, building renovations, and accidental sediment spills can be substantial contributors to contemporary sediment yield in mature suburban watersheds. A similar pattern of relatively large sediment yield was found from storm sampling in a nearby mature suburban watershed tributary to Triadelphia Reservoir (Smith, 2011).

4.2. Sediment yield at fifth-order

Triadelphia Reservoir is located on the fifth-order Patuxent River. Three of the upland basins (1, 3, 4) drain to the reservoir and the remaining three are in close proximity and have similar physiographic settings (Reger and Cleaves, 2008). Total sediment yield to Triadelphia Reservoir was 142 Mg/km^2/y over the period 1943 to 2005 (Fig. 6). This value is averaged over the 63-year life of the reservoir at the time of surveying and is based on volumetric change by Ortt et al. (2008a) using estimates of the original reservoir topography derived by OSI (1997). Volume was converted to mass using a bulk density of 894 kg/m^3, the weighted average of core samples from a previous survey (OSI, 1997). Ground surveys were conducted in reservoir tributary confluence areas in order to include areas too shallow for boat access, documenting an additional volume that amounts to <5% of the total sediment accumulation in the impoundment.

Comparison of sediment yield at fifth-order with upland contributions requires accounting for the area of the different land cover types in the watershed (Table 3). Values used here are 52% agriculture (primarily row crops), 33% forest, and 15% suburban derived from the Maryland Department of Planning (MDP) land cover data sets with metadata documentation from 1994 and 1997 summarized by the Patuxent Reservoirs Modeling Group (PRMG, 2000). A relatively small area, 0.2% of the UPRW area, is assigned to annual land construction disturbance activity based on the calculated average rate of development that occurred over the lifespan of the reservoir.

Despite the general trend of ongoing conversion of rural to suburban land uses in the Baltimore — Washington corridor, changes in the UPRW were limited over the period of reservoir sediment accumulation. The persistent land cover is largely caused by interest in protecting the public drinking water supply provided by the Patuxent reservoirs. The MDP spatial data shows that <15% of the UPRW transitioned from agriculture to low density residential lots or forest from 1973 to 2002, a time span that includes the year of the land cover estimates used in our analysis. Sediment yield calculated using the 1973 and 2002 data differ by only 2%. Land disturbances from infrastructure improvements, particularly work on an interstate highway along the northern edge of UPRW, likely generated relatively high sediment loadings for brief periods of time without recorded changes in land cover along their respective corridors.

A geomorphic analysis by Smith (2011) estimated that first-order basins occupy 62% of the watershed (Fig. 7). Other non-channeled upland areas drain 35% of the watershed directly into tributaries of second-order or higher. The delineations and application of separate SY values for zero- and first-order watersheds are required to account for sediment contributions from erosion or storage in upland channels (Table 3). The remaining 3% of the watershed consists of alluvial valley floodplain area.

Observed rates of sediment yield, distinguishing between zero- and first-order basins, are used to cumulate sediment yield to the drainage area of the Triadelphia Reservoir. We use 66 Mg/km^2/y for SY from

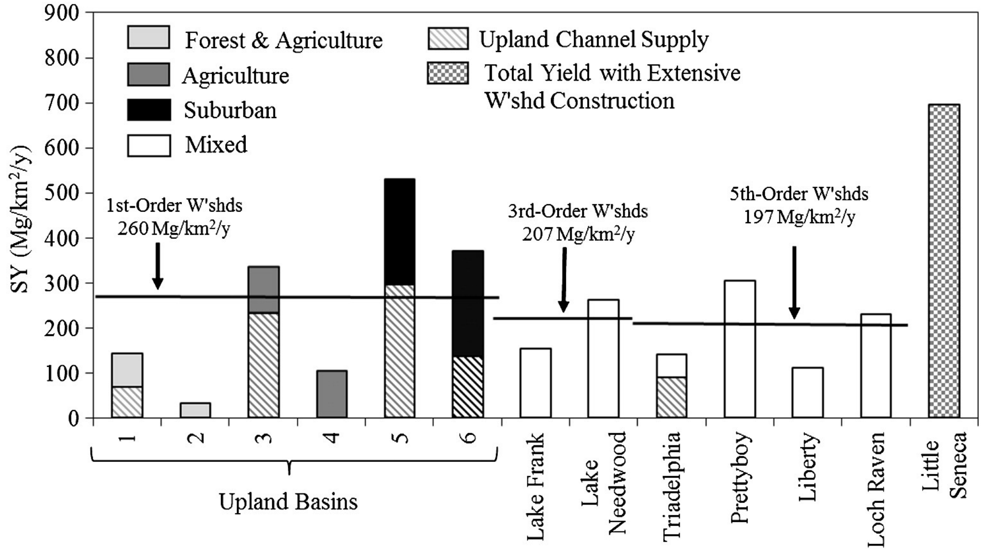

Fig. 6. Sediment yield calculated from measured impoundment sedimentation at the outlets of upland and lowland tributaries. Upland (first-order) channel supply is estimated using the following sediment yield ratio ($SYR_1 = SY_1/SY_0$) values derived from measurements: Forest = 1.91, Suburban = 2.26, Agriculture = 3.25, Mixed = 2.7. Only total yield is provided for basin 2. Upland channel supply at the scale of higher order watersheds is estimated only for the UPRW (using sedimentation measurements from small ponds and Triadelphia Reservoir) and the *SYR* for the mixed land cover condition.

non-channeled forested lands, calculated as an area-weighted average of values from basins 1 and 2. This value is identical to the EOF value for Piedmont forests reported in the National Resources Inventory (NRI) (NRCS, 2007; USEPA, 2009) and slightly smaller than the maximum yield from forested plots suggested by Patric et al. (1984; 72 Mg/km^2/y). Field observations of concentrated overland flow and sediment transport suggest that substantial sediment yield from forested slopes can occur. The SY from first-order forested basins, 119 Mg/km^2/y, is also calculated as an area-weighted average of values from basins 1 and 2; and the larger value primarily reflects contributions from the estimated channel enlargement in basin 1.

The SY from agricultural land, based on observations from basins 3 and 4, is 103 Mg/km^2/y for non-channeled uplands and 336 Mg/km^2/y from first-order watersheds. These values are small compared to NRI estimates for cropland EOF, which are generally >1000 Mg/km^2/y, and include, at least in part, the influence of functioning grassed waterways in basins 3 and 4. Although Costa (1975) showed that other sources of upland colluvial storage exist, the large difference between the values used here and the NRI values suggests that our estimates of SY from cropped uplands may be a lower bound.

We apply a SY from suburban land of 234 Mg/km^2/y for upland areas (basin 5) and 427 Mg/km^2/y for first-order suburban watersheds, the area-weighted averages from basins 5 and 6. These rates are larger than those used for forested and agricultural land cover and are consistent with storm measurements made in a different suburban watershed in a similar setting (Smith, 2011).

A value of 2102 Mg/km^2/y is used for SY from areas disturbed by construction. This value is based on the observation of 8408 Mg/km^2/y in a 0.24-km^2 watershed by Wolman and Schick (1967) and assuming a 75% efficiency of sediment control practices (Schueler and Lugbill, 1990). Although the value of SY is very large, the fraction of disturbed area is small, such that sediment contributions from disturbed areas are only 2% of the total sediment yield from UPRW.

The land-cover weighted SY in the UPRW, upstream of Triadelphia Reservoir, is 215 Mg/km^2/y, which is 50% larger than the SY of 142 Mg/km^2/y observed in Triadelphia Reservoir. Although considerable extrapolation is required to develop a spatially modeled estimate, the value presented here has the benefit that it is based on long-term yield measured in ponds draining upland watersheds with rather homogeneous and temporally stable land cover. The choices we made in

Table 3
Upland sediment yield in Upper Patuxent watershed.

Land condition/setting	Watershed (%)	Sediment yield zero order (Mg/km^2/y)	Sediment yield first order (Mg/km^2/y)
Agricultural	52	103	336
Forest	33	66	119
Suburban	15	234	427
Construction	0.2	2102	2102

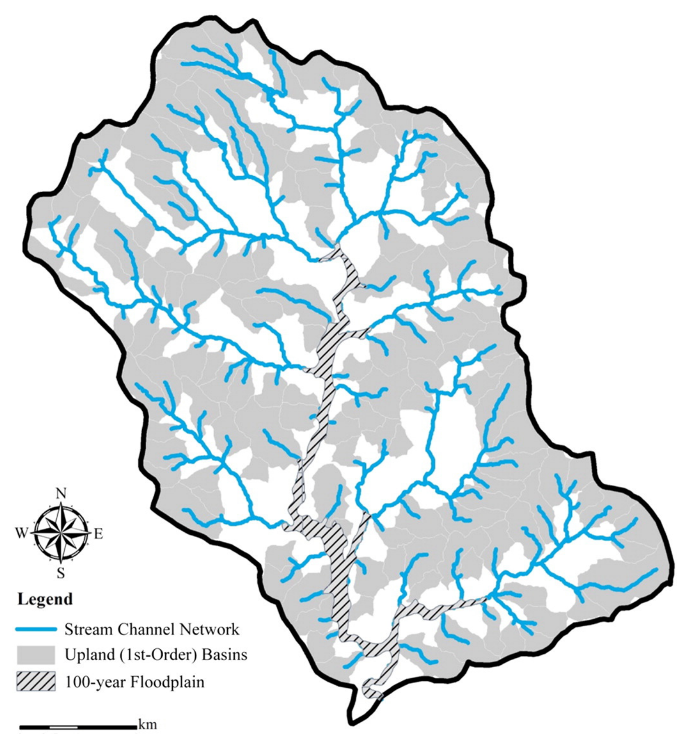

Fig. 7. Map of the Cattail Creek watershed within the UPRW. Shaded areas represent first-order basins with upland channels. Nonshaded portion of the watershed represents nonchanneled hillslopes and zero-order basins draining directly to streams of second-order or higher. Floodplain delineation is based on the delineation by FEMA (2003).

selecting upland SY values and comparison to other reports suggest that our estimates of upland supply may be conservative, such that the reduction in sediment yield from upland watersheds to fifth-order is *at least* one-third. Possible sources of larger upland supply include: poorly maintained or absent urban sediment controls and agricultural best management practices, channel erosion downstream from locations of active construction, and poorly documented construction activities related to highway improvements along the northern UPRW border.

A decrease in SY with increasing drainage area is consistent with that generally reported in the literature (Roehl, 1962; Leopold et al., 1964; Vanoni, 1975; USDA, 1983). The amount of the decrease in SY in any particular mid-Atlantic Piedmont watershed will depend on watershed conditions, including the mix and spatial distribution of land cover types, geologic controls that govern channel erosion and water flows within valleys, and the presence of engineered structures such as small dams and roadway culverts. Interestingly, our value of a one-third reduction in SY from first- to fifth-order is similar to the value of 31% reported by Scatena (1987) for the cumulative upland sediment supply relative to sediment yield on the fifth-order Anacostia River watershed immediately south of the UPRW.

4.3. Reservoir accumulation in other Piedmont watersheds

The SY in Prettyboy Reservoir, which is comparable in drainage area to Triadelphia, is 321 Mg/km^2/y, more than twice that of Triadelphia (Fig. 6; Table 2). The SY to the larger Loch Raven Reservoir, which is a record complicated by the presence of the upstream Prettyboy Reservoir over nearly all of its lifespan, is 230 Mg/km^2/y, also larger than that of Triadelphia. Liberty Reservoir, geographically closer to Triadelphia but draining a larger area, has a smaller SY (118 Mg/km^2/y). All of the reservoirs occupy fifth-order channels draining dominantly Piedmont terrain and have a similar distribution of land cover, composed in decreasing order of agriculture, forest, and suburban development. The average SY for Triadelphia, Prettyboy, and Liberty Reservoirs is 197 Mg/km^2/y with an overall range of a factor of 2.7. All of the reservoirs have been in existence for nearly half a century or more, a time period that included the flood of record for many areas in the region caused by Hurricane Agnes. The influence of that single event was evaluated in a previous survey in Triadelphia Reservoir, finding no discernable effect from the storm on the sedimentation record (EA Engineering, 1989).

The SY from two nearby reservoirs on third-order streams is 148 Mg/km^2/y for Lake Frank and 278 Mg/km^2/y for Lake Needwood, with an average of 213 Mg/km^2/y. This is only slightly larger than the average for the fifth-order reservoirs, suggesting little apparent decrease in SY from third- to fifth-order. An important exception is Little Seneca Lake, located immediately to the southwest of the UPRW, which has an SY of 695 Mg/km^2/y based on measurements by OSI (1997) (Fig. 6; Table 2). Sedimentation was recorded for 1996 to 1983, a period of aggressive suburban expansion and extensive highway construction along the I-270 corridor northwest of Washington DC. Although a detailed time series of the extent of land disturbance is not available, the larger SY can be accommodated using our upland SY values and the observed land-cover distribution (approximately 25% suburban and agricultural and 40% forest) by assigning 12.5% of the watershed area to construction disturbance with sediment controls operating at 50% efficiency, a plausible performance rate for large construction projects. Although these values are only indicative, they are consistent with the many observations of extensive sediment yield from construction areas.

5. Discussion

5.1. Comparison to other estimates of sediment yield

Comparison with other calculations of sediment yield in the mid-Atlantic Piedmont provide context for our observations in the Patuxent watershed. The only complete sediment budget in the region was developed for the Good Hope tributary to the Paint Branch of the Anacostia River for the period 1951 to 1996 by Allmendinger et al. (2007). This is a small (4 km^2), third-order watershed that underwent suburban development over this period. Upland supply was estimated from land cover records and upland rates reported by Yorke and Herb (1978) and from surveys of first-order channels. Sedimentation and erosion rates were measured for the valley bottom area and sedimentation was found to exceed erosion by 25%. Total sediment load was determined as a residual by subtracting sediment storage from the upstream and channel erosion input terms, giving SY = 135 Mg/km^2/y. This rate is very close to that observed for the larger Triadelphia watershed, but is smaller than the suburban sediment yield values we observed in upland ponds.

Fig. 8 shows annual SY based on sediment flux measurements at various USGS gages in the Piedmont of the Chesapeake Bay watershed, along with pond and reservoir values from this study as well as several other reservoirs in the region. The USGS gage values are taken from Gellis et al. (2009) and Schenk et al. (2013). Most of the sediment load estimates were developed from samples collected in a small number of years and then extrapolated to the periods 1952–1984 and 1985–2001 using continuous flow gaging records. Details on the different periods of record can be found in the original references. The reliability of sediment load estimates from gage station measurements can be quite variable owing to uncertainties related to sampling technique and extent, omission of bedload samples, methods of calculation and nonstationarity (Walling and Webb, 1981; Walling, 2008). Notwithstanding, SYs from smaller watersheds (DA < 20 km^2) fall in the range 100 to 400 Mg/km^2/y and are comparable to the pond and reservoir values reported in this paper. Sediment sampling for these smaller watersheds was conducted in the 1970s in the Reston, VA area (an urbanizing suburb of Washington DC) and in the 1980s in Little Conestoga Creek, PA (a predominantly agricultural and forested watershed at the time).

In a middle range of watershed size (20 km^2 < DA < 140 km^2), two values of SY greater than 100 Mg/km^2/y and five values between 14 and 70 Mg/km^2/y are reported from USGS gages. The gages in this range of drainage area include four from suburban Washington DC in the 1970s and a tributary to Little Conestoga Creek in the 1980s. The SY for the Unity gage on the Patuxent River is 14 Mg/km^2/y. This value is of particular interest because the gage is located immediately above Triadelphia Reservoir and measures slightly more than half the reservoir drainage area, yet the reported SY is an order of magnitude smaller than that determined from reservoir sedimentation. The Unity estimate is based on suspended sediment observations in 4 y, and the difference may be attributed to relatively small flows or loads in those years. Average annual sediment yield for the Patuxent River at Bowie, MD, downstream from the Triadelphia and Rocky Gorge Reservoirs, is also relatively small (41 Mg/km^2/y for the period 1985–1999). Yield at the station is calculated from suspended sediment loads estimated using concentration samples collected at the USGS gage on the Patuxent River near Bowie, MD. Annual loads derived from the USGS data have an average statistical error of 16% and also carry uncertainty from limited sampling despite having a more extensive record than the Unity station (Yochum, 2000). The yield derived from measurements is calculated with the assumption that the two upstream reservoirs capture all of the sediment delivered from their drainage areas, leaving 62% (559 km^2) of the watershed downstream from the Rocky Gorge Reservoir as the sediment source to the gage. Although most of the drainage area to the Bowie gage is from the Piedmont, the station is located in the Coastal Plain physiographic province and the small SY may reflect increased sedimentation along a valley bottom that is generally wider and more gently sloped.

For the 10 Piedmont gages with drainage area > 140 km^2, all SYs are small, with none exceeding 61 Mg/km^2/y. Although reservoir observations suggest that SY remains relatively large up to 568 km^2 (Loch

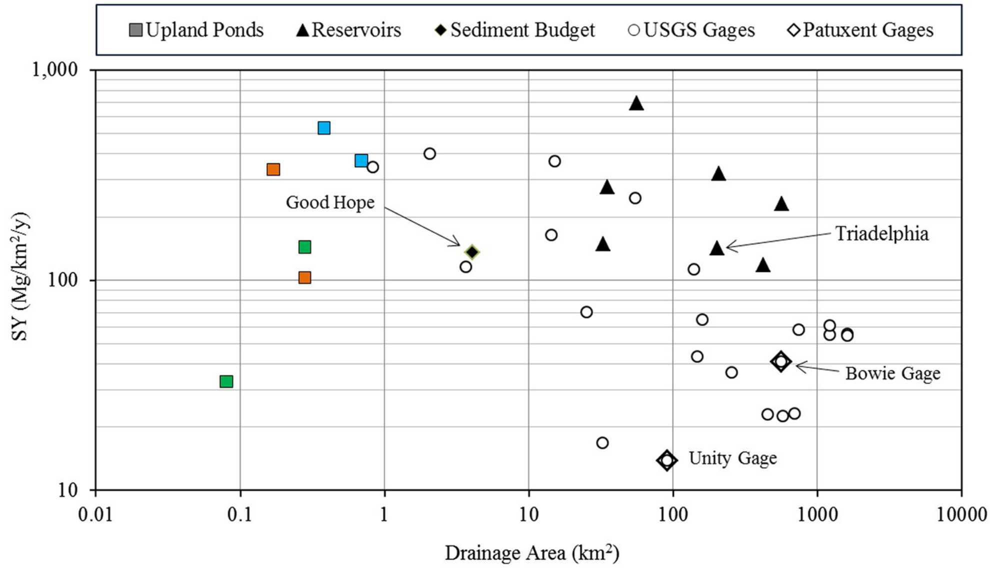

Fig. 8. Piedmont annual sediment yield comparison, including estimates from upland ponds and reservoirs from this study (UPRW upland values include agriculture (*orange*), forest (*green*) and suburban (*blue*) dominant land cover), sediment budget from Allmendinger et al.(2007), and USGS gage values from Gellis et al. (2009) and Schenk et al (2013). Bowie gage on Patuxent River is located in Maryland's Coastal Plain downstream from the Piedmont Province. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Raven Reservoir, whose sediment supply is presumably moderated by the presence of Prettyboy Reservoir upstream), results based on gaging are persistently much smaller. This consistent difference in SY between reservoir and gage estimates suggests that the discrepancy cannot be explained only by sediment sampling during years with unusually low flow and that methodological differences may be important. These may include assumptions required to extrapolate sampled suspended sediment concentrations over long time periods and larger, unsampled flows. The very large difference in SY for the Triadelphia Reservoir compared to the estimate developed from the Unity gage indicates that large discrepancies are possible between gage estimates for a limited time period and long-term reservoir accumulations. The increasing use at gages of continuous records of sediment surrogates such as turbidity and acoustic reflection offers an important opportunity to evaluate methods used to develop long-term sediment yield estimates for short-term gage records.

5.2. Comparison to net storage in alluvial valley bottoms

The difference between cumulative sediment supply from zero and first-order watersheds and accumulation in the fifth-order Triadelphia Reservoir represents net sediment storage along second- and higher order valley bottoms. Explicitly, an annual sediment budget can be defined as

$$U + E - S = L \tag{1}$$

where U is upland supply, E and S are erosion and sedimentation along higher order streams, respectively, and L is sediment delivery at the watershed outlet. We define the budget on an annual basis and terms have units Mg/y. Note that U is the *net* sediment supply from uplands and hence includes colluvial storage and net channel enlargement. In the mid-Atlantic Piedmont, upland watersheds include most zero- and first-order streams as well as some smaller second-order streams (such as those draining to basins 5 and 6) with steep slopes and little floodplain storage. The boundary between upland and lowland streams is not sharp.

Observations of S and E on Piedmont streams have been made by Schenk et al. (2013), including in Difficult Run, a Piedmont tributary on the Virginia side of the Potomac in a physiographic setting very much like the UPRW. Observation of S and E by Schenk et al. do not define the physical extents of their study areas and direct comparison to our observations of U and L in the UPRW is not possible because $U - L$ applies to the entire watershed, whereas $S - E$ is determined for individual sites. Comparison between the two measures, expressed as a length (mean thickness of erosion or deposition) can be achieved if $(U - L)$ is divided by the valley bottom area in the Triadelphia watershed area and $(S - E)$ is divided by the area of the individual study sites in Schenk et al. Placing the two quantities in common units of length is for the purpose of comparison and does not imply that the two should be equal.

We approximate the extent of the UPRW alluvial valley lowland area using the 100-year floodplain delineation by FEMA (2003). Lowland deposits may extend farther upstream in some third-order tributaries, although the additional area is relatively small because of the narrowing of the valley width with upstream distance. Sediment storage over multidecadal time scales has been observed to be relatively small in narrow Piedmont valleys (Wolman, 1987).

The difference between the upland supply and Triadelphia accumulation is 14,900 Mg/y. When distributed over an approximately 6.1-km^2 valley bottom area, the net storage corresponds to a mean vertical accretion rate of 2.6 mm/y using an average bulk density of 0.94 Mg/m^3 reported for Piedmont floodplains by Schenk et al. (2013). The net deposition will, of course, vary with location, and we do not attempt here to differentiate between deposition in the active channel versus overbank locations.

Schenk et al. (2013) reported values of S and E as kg/m/y for five study sites in Difficult Run. Using the mean of their reported values of bulk density (0.94 Mg/m^3) gives values of net sedimentation rate of −2.4, 1.1, 6.9, 6.5, and 2.0 mm/y, with a mean of 2.8 mm/y. This value of net valley bottom deposition is very similar to that which we calculate (2.6 mm/y) for the Patuxent watershed.

The net valley bottom sedimentation for the Good Hope sediment budget is likely smaller than these values because sedimentation and erosion rates were estimated to be comparable ($S = 4000$ m^3/y; $E = 3200$ m^3/y). Allmendinger et al. (2007) reported valley bottom sedimentation rates between 0.7 and 2.0 mm/y based on timing and deposition thickness determined from dendrochronology. Including erosion rates of 80% of S gives a net valley bottom sedimentation smaller than 1 mm/y.

Although the contemporary net valley bottom accumulation rates reported here are consistent with the observations in Difficult Run, they are likely small relative to historic rates during periods of widespread cropping with minimal conservation practice. Happ (1945) observed an average accumulation thickness of agricultural age sediment of approximately 1.22 m over an estimated time period of 150 y immediately prior to the mid-twentieth century, which equals a lowland deposition rate of 8.1 mm/y in the South Carolina Piedmont during a time period mostly pre-dating the observations summarized here. Costa (1975) observed 0.81 m of accumulation after 1924 in the floodplain of Western Run in Maryland's Piedmont, giving an aggradation rate of 16.3 mm/y. Large valley bottom accumulation rates are not exclusively limited to the nineteenth and early twentieth centuries, however. Leopold et al. (2005) observed accumulation of floodplain sediment of approximately 0.30 m over a 41-year time period ending in 1993 in the Watts Branch floodplain located just south of the UPRW. The sedimentation rate of 7.4 mm/y is nearly three times that for the Patuxent and corresponds to a period of intense urbanization in Rockville, MD, further suggesting that persistent land disturbance sharply increases sediment yield.

5.3. Proportion of sediment load from lowland valley bank erosion

A pressing question of fundamental and applied importance concerns the source of fine sediment delivery (L) from coastal watersheds. Management efforts to reduce sediment loading aim to locate those sediment sources that most directly contribute to delivery from the watershed. Most practically, evaluation of how reductions in either lowland bank erosion (E) or sediment supply from upland basins (U) will contribute to reductions in L is useful. A complete sediment budget provides just this information, but information on all components of the budget is frequently not available. If only part of the information is available, a determination of the fraction of L that is from uplands (U) or lowlands (E) is difficult. For example, if information is available on only upland supply, the fraction of that supply that is actually delivered from the watershed will depend on the rate of lowland erosion and on the rate of lowland sediment storage.

If valley bottom storage is active in the Piedmont — as suggested by Scatena (1987), Allmendinger et al. (2007), and Schenk et al. (2013) — upland sediment supply (or any reductions in it) may cycle through valley bottoms and require long time periods before reaching the Chesapeake Bay (Pizzuto et al., 2014). The potential for long lag times between management action and change in load to the Bay has become a prominent challenge for managing the Chesapeake TMDL programs (STAC, 2013). Here, we evaluate how incomplete or generalized information about sediment sources and sinks might be used to constrain estimates of the relative contribution of different sources to watershed sediment delivery.

Because all parts of the budget are linked by the strong constraint of sediment mass conservation, we can frame the linkage between upland (U) and lowland (E) sediment supply and delivery (L) in ways that can take advantage of available information. Of particular interest are cases in which information on net supply is available only for uplands or lowlands, and the question remains as to which source may be the larger component of sediment delivery L. First, Eq. (1) is arranged as

$$U–L = S–E \tag{2}$$

which leads to the observation (useful below) that, if U is larger than L (as required for a typical sediment yield ratio $SYR = L/U < 1$), then S must be greater than E. Factoring out L and E in Eq. (2) gives

$$L\left(\frac{U}{L}-1\right) = E\left(\frac{S}{E}-1\right). \tag{3}$$

Rearranging, the magnitude of E with respect to L is

$$\frac{E}{L} = \frac{(U/L)-1}{(S/E)-1}. \tag{4}$$

This relation gives the magnitude of E relative to L, which depends on U/L and on S/E. For cases in which U/L can be estimated, any knowledge of the value of S/E can be used to constrain the possible range of E/L. If information on lowland storage and erosion (S/E) is available, an estimate of the range of likely U/L constrains the range of E/L. Although Eq. (4) gives the magnitude of E relative to L, its proportion in the actual load L depends also on the magnitude of U because U and E can be stored in the valley bottom. A better constrained measure would be the magnitude of E relative to the total sediment supply ($E + U$):

$$\frac{E/L}{(E+U)/L} = \frac{\left[\frac{(U/L)-1}{(S/E)-1}\right]}{(U/L) + \left[\frac{(U/L)-1}{(S/E)-1}\right]} \tag{5}$$

which can be rearranged as

$$\frac{E}{E+U} = \frac{1-SYR}{S/E-SYR}. \tag{6}$$

Thus, the proportion of E in the total supply can be determined as a function of S/E and sediment yield ratio SYR ($SYR = L/U$). Part of the utility of this expression is that the proportion E in the total supply depends on the ratios SYR and S/E and not on the individual values of U, L, S, and E. Fig. 9A provides solutions for $E\,/\,(E + U)$ as a function of SYR for various values of S/E. Fig. 9B provides solutions for $E\,/\,(E + U)$ as a function of S/E for various values of SYR. One sees that $E\,/\,(E + U)$ decreases with an increase in either SYR or S/E. For example, for $SYR = 0.5$, Fig. 9A indicates that $E\,/\,(E + U)$ is 0.5 for $S/E = 1.5$ and decreases to 0.1 for $S/E = 5.2$, which corresponds to the mean value for measurements made in Difficult Run. For $S/E = 2$, Fig. 9B indicates that $E\,/\,(E + U)$ is 0.45 for $SYR = 0.2$ and decreases to about 0.08 for $SYR = 0.91$, which corresponds to the SYR value determined for the Good Hope tributary.

An interesting observation from Eq. (6) is that E can be a large proportion of the total sediment supply only if the value of S/E is small relative to the values reported for Difficult Run by Schenk et al. (2013). Values of $E\,/\,(E + U)$ in excess of one-half require values of $S/E < 2$. For $SE = 2.6$ (one-half the mean value for Difficult Run), E can be no more than 25% of the total supply if SYR is larger than 0.5. The contribution of *legacy* sediment (or any other component of lowland valley bottom erosion) to sediment delivery is simply the proportion of E that is legacy sediment derived from human disturbance to the landscape (James, 2013).

Fig. 9 allows for some interpretation of particular cases. A value for Good Hope Tributary is located using $S/E = 1.25$ (based on independent observations of S and E from channel surveys and dendrochronological observations of sedimentation) and $SYR = 0.91$ (U is estimated from rates of upland sediment supply, historical land cover, and surveys of first-order channels; and L is determined as a residual from individual values of U, S, and E). This combination shows that the lowland proportion of the sediment supply is 26%. Allmendinger et al. (2007) indicated that legacy sediment composed about half of the eroding stream banks, giving a contribution to load from legacy sediment of 13%.

The use of Eq. (6) and Fig. 9 for cases with incomplete information can be shown for the examples of Difficult Run and the Patuxent watershed. For the mean value of $S/E = 5.2$ for Difficult Run, the lowland proportion of the supply is necessarily small, regardless of SYR (Fig. 9B). For the Triadelphia watershed, $SYR = 0.66$, and the lowland proportion of sediment supply can be evaluated as a function of S/E. If the Difficult

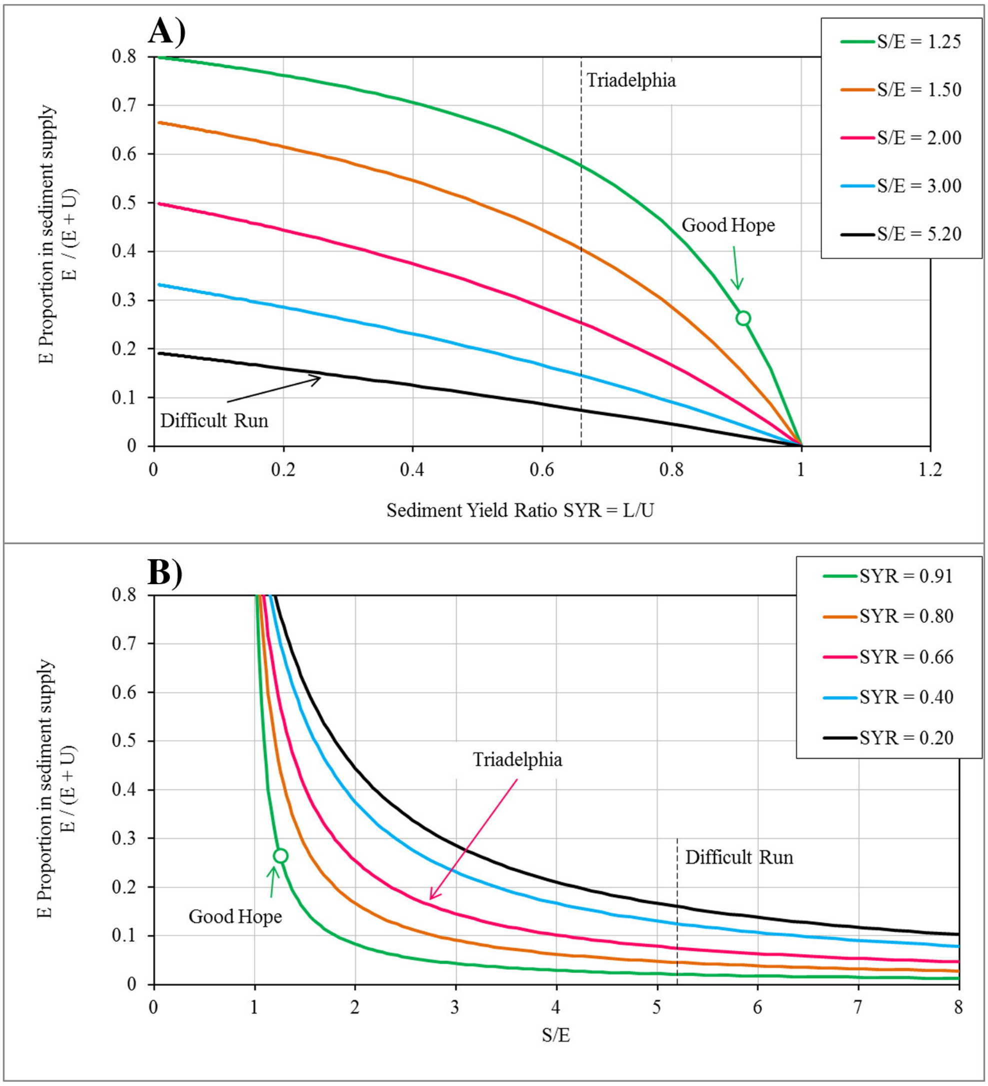

Fig. 9. Proportion of sediment from lowland valley erosion (E) contained in the total sediment supply ($E + U$), as a function of sediment yield ratio SYR (L/U) and ratio of valley bottom storage to erosion (S/E). Based on the annual sediment budget (Eq. (6)). Plots are limited to the case for which sediment yield ratio $SYR < 1$, which requires that $S/E > 1$. (A) $E / (E + U)$ as a function of SYR for a family of S/E curves. (B) $E / (E + U)$ as a function of S/E for a family of SYR curves. Value for Good Hope tributary sediment budget (Allmendinger et al., 2007) is shown. Only SYR is known for Triadelphia Reservoir and only S/E is known for Difficult Run (Schenk et al., 2013), and the figure shows how a sediment budget can be used to constrain the value of $E / (E + U)$ based on limited information.

Run value of S/E is applied to Triadelphia, E is about 7% of the total supply. Even a much smaller value of $S/E = 2$ corresponds to lowland proportion of the supply equal 25%. Any contribution from agricultural era legacy sediment would be a fraction of that.

6. Conclusions

Observations of sediment accumulation in ponds and reservoirs provide a reliable estimate of sediment yield over periods of decades and longer. We report on sediment yield for six upland (zero- and first-order) watersheds in the Patuxent River watershed draining the Piedmont physiographic region of Maryland, USA. Each watershed was dominated by one land cover over the life of the pond, with two each in suburban, forest, and agricultural land cover. Sediment yield from suburban first-order watersheds was the largest of the three land classes, with 234 $Mg/km^2/y$ from zero-order and 427 $Mg/km^2/y$ from first-order watersheds. Although enlargement of stream channels contributes part of this sediment load, one-half to two-thirds of the sediment load was derived from sources outside of the stream channel. This provides evidence that suburban upland areas do not become sediment *starved* in the decades following initial construction. Sediment yield from two agricultural watersheds was 103 $Mg/km^2/y$ for zero-order and 336 $Mg/km^2/y$ for first-order watersheds. This is smaller than the suburban value and much smaller than edge-of-field estimates often used in estimating sediment supply. These values may reflect, at least in part, the presence of well-functioning grassed waterways, which can act to reduce sediment loading. Sediment yield from the two forested watersheds was the smallest, with 66 $Mg/km^2/y$ for zero-order and 119 $Mg/km^2/y$ for first-order watersheds. Enlargement of first-order stream channels clearly plays an important, but not exclusive role in sediment yield from upland watersheds. Channel enlargement was estimated to contribute between one-third and two-thirds of the sediment load over the life of those ponds draining a watershed with a first-order channel.

We compared upland sediment yields to sediment accumulation in Triadelphia Reservoir, located on a fifth-order river channel. Sediment yield based on accumulation in the reservoir was 142 $Mg/km^2/y$, which is two-thirds of our estimate of upland supply, indicating net storage in the valley bottoms of second- to fifth-order streams. Sediment yield based on surveys of other reservoirs in the Maryland Piedmont range between 118 and 321 $Mg/km^2/y$. Sediment yields for two reservoirs on third-order streams were comparable to the larger reservoirs at 148 and 278 Mg/km^2/y. An exception is a reservoir draining a watershed that underwent aggressive development and extensive highway construction. Sediment yield for this reservoir was 695 Mg/km^2/y, indicating the large impact of construction disturbance on sediment loads.

Sediment yields estimated from sediment sampling at stream gages are comparable to those from ponds and reservoirs (SY > 100 Mg/km^2/y) for watersheds smaller than 20 km^2. For drainage areas larger than 140 km^2, sediment yield from reservoirs is consistently larger (118 to 321 Mg/km^2/y with mean 200 Mg/km^2/y) than sediment yield from stream gages (22 to 65 Mg/km^2/y with mean 45 Mg/km^2/y). This suggests that the different methods provide very different estimates of sediment yield. This possibility is reinforced by the fact that sediment yield estimated from a gage immediately above the Triadelphia Reservoir (and draining nearly half the watershed area) was an order of magnitude smaller than the sediment yield based on reservoir accumulation.

The general observation of decreasing sediment yield with drainage area indicates net storage of sediment along the valley bottoms of higher order streams. Observations of valley bottom sedimentation and erosion indicate that contemporary valley bottoms act as sediment traps despite the history of storage documented for previous time periods (Happ, 1945; Costa, 1975; Jacobson and Coleman, 1986). Net sediment storage in the UPRW valley bottom, estimated as the difference between upland supply and reservoir accumulation divided by valley bottom area was 2.6 mm/y. This value is very similar to that determined for multiple study sites in Difficult Run, a watershed of similar size in a similar physiographic setting in northern Virginia. In the case of Difficult Run, values of valley bottom sedimentation and erosion were determined by direct measurement of bank erosion and valley bottom sedimentation along five study reaches.

Evaluation of the sediment mass balance among upland supply, valley bottom sedimentation, stream bank erosion, and watershed delivery shows that rates of sedimentation must exceed rates of bank erosion if sediment delivery from the watershed is smaller than the rate of sediment supply from upland valleys, as is generally the case. If rates of sedimentation greatly exceed sediment supply from erosion in valley bottoms, as indicated by recent studies, then the proportion of sediment delivery from the watershed that is derived from stream banks is likely to be small.

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