BANK EROSION IN FIFTEEN TRIBUTARIES IN THE GLACIATED UPPER SUSQUEHANNA BASIN OF NEW YORK AND PENNSYLVANIA

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Abstract: The proportional contributions of cultivated lands and stream banks as sources of fine sediment loads were quantified in 15 rural watersheds in the Glaciated Appalachian Plateau region of the Susquehanna River basin of New York and Pennsylvania. We utilized a relatively simple method of fingerprinting sediment sources by comparing the concentrations of the nuclear bomb–derived radionuclide ^{137}Cs in fluvial sediment samples collected from channel margins with sediment from cultivated fields and stream banks. The proportion of fine sediment from bank erosion ranged from none to 100% in the study tributaries, with a median contribution of 53% across the 15 study streams. In one stream with no evidence of bank sediment, anomalously high ^{137}Cs levels in the samples indicated that the sources were pasture or forest, probably scoured from marshy floodplains upstream of the sampling sites. In the 14 other streams, cultivated lands accounted for an average of 42% of the fine sediment. We discuss sources of eroded bank material and the processes driving stream bank erosion in this glaciated region, and examine the impact of historic mill-dam deposits on bank erosion. [Key words: stream bank erosion, sediment sources, sediment tracers, ^{137}Cs, glaciated upper Susquehanna basin, mill dams, legacy sediment.]

INTRODUCTION

The Susquehanna River basin is the largest on the Atlantic seaboard and the largest draining into the Chesapeake Bay. The Susquehanna's 71,225 km^2 watershed drains portions of New York, Pennsylvania, and Maryland before emptying into the head of Chesapeake Bay, where it provides about half the Bay's fresh water and about

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22% of the Bay's sediment load (Upper Susquehanna Coalition, 2005). Much of the habitat of Chesapeake Bay is degraded due to excess sediment deposition (Gellis et al., 2004). There is little understanding of the dominant processes influencing fine sediment yields in the glaciated Upper Susquehanna basin. An examination of sediment sources in this region adds an important perspective on sediment-generating processes applicable to a much wider glaciated region of North America. With the exception of a few studies (Campo and Desloges, 1994; Sekely et al., 2002; Riedel et al., 2005; Nagle et al., 2007), little research has addressed the water quality issues associated with erosion of glacial drift in North America.

Many agencies in the United States are grappling with mandates from the U.S. Environmental Protection Agency to greatly reduce sediment loads, although there have been disagreements (i.e., Trimble and Crosson, 2000) on the estimates for the contribution of agricultural erosion to sediment loads. Commonly used surface erosion–based models, such as the Universal Soil Loss Equation and its derivatives, have not proven effective in explaining sediment-generating processes and sediment yields in the Chesapeake Bay watershed (Boomer et al., 2008). Until recently, it was assumed that about two-thirds of the sediment load in the Upper Susquehanna was from agricultural erosion (Upper Susquehanna Coalition, 2006). However, unlike sediment yields of unglaciated river basins flowing in the Atlantic drainage of the U.S., Meade (1982) observed that the percent of cropland had no bearing on total sediment yields from the glaciated Susquehanna basin.

Large contributions of stream bank erosion to sediment loads have been reported in other regions of North America (i.e., Odgaard, 1987; Campo and Desloges, 1994; Glasman, 1997; Brigham et al., 2001; Sekeley et al., 2002; Nagle and Ritchie, 2004, Reidel et al., 2005; Nagle et al., 2007). Stored post-settlement alluvial deposits, referred to now as "legacy sediments," have been documented as major sediment sources in the upper Midwest (Trimble, 1983), the Southeast (Phillips, 1991), the Columbia Plateau of Oregon (Nagle and Ritchie, 2004), and the southern Susquehanna basin (Walter and Merritts, 2008).

It is not clear what role the erosion of legacy sediments plays in the Upper Susquehanna. Accelerated stream bank and channel erosion are recognized problems in the southern Susquehanna basin (Walter and Merritts, 2008). The Conestoga watershed in southeastern Pennsylvania has the highest sediment yields (279 t km^{-2} yr^{-1}) in the entire Susquehanna basin, with one tributary yielding 827 t km^{-2} yr^{-1} (Gellis et al., 2006). Much of the eroding alluvium in this area of the lower Susquehanna is "legacy sediments," deposited on floodplains as long ago as the early 18th century, much of it behind mill dams (Walter and Merritts, 2008).

This study examines the contribution of bank erosion in a suite of 15 rural tributaries in the glaciated Upper Susquehanna. We discuss the processes driving bank erosion in this region, examine the effects of legacy sediments and early settlement-era mill dams on sediment storage and bank erosion, and compare sediment-generating processes to those previously documented for the southern Susquehanna basin.

BACKGROUND: SEDIMENT TRACERS

Sediment provenance can be determined by comparing the properties of samples collected from streams with those of soils in potential source areas such as agricultural fields, forests, and channel banks. A number of methods have been used to fingerprint source areas of fluvial sediment. These include particulate phosphorus (Hasholt, 1988), mineral magnetic measurements (Slattery et al., 1995), the identification of clay minerals (Youngberg and Klingeman, 1971; Glasman, 1997), and sediment carbon and nitrogen (Peart and Walling, 1986; 1988). Mixing models are used to identify the relative contribution of different sources (Foster and Lees, 2000). Successful use of bomb-derived and natural radionuclides in sediment tracer work has been widely reported (Wallbrink, et al., 1998; Nagle and Ritchie, 1999, 2004; Brigham et al., 2001, Matisoff et al., 2002a; Whiting et al., 2005).

Multiple-tracer approaches have been applied to trace sediments (Walling et al., 1993; Collins and Walling, 2004). These approaches are most appropriate when distinguishing between more than two sediment sources or more geologically complex watersheds, and even then discrimination can be relatively poor (Owens and Walling, 2002). Simple mixing models have used just ^{137}Cs to distinguish between bank/gully walls and upland surface sources of sediments (Zhang et al., 1995, 1997; Wallbrink et al., 1998; Brigham et al., 2001; Nagle and Ritchie, 2004; Walling, 2004; Nagle et al., 2007). Without the use of mixing models of any kind, Froehlich and Walling (2005) used ^{137}Cs to delineate sediment from surface soils and deep roadcuts. ^{137}Cs is one of the most conservative tracers in use compared to almost all other tracers (Davis and Fox, 2009; Juracek and Ziegler, 2009) for distinguishing bank sediment. Devereux et al. (2010) found that ^{137}Cs was the single tracer out of 63 elements and two radionuclides that was able to distinguish between bank and floodplain surface sediments, although Fox (2009) was also able to use ^{15}N as a single tracer to distinguish between bank and surface sediment.

Atmospheric nuclear tests in the 1950s and early 1960s distributed radioactive fallout ^{137}Cs around the globe. ^{137}Cs was deposited in precipitation and adsorbed by soil, where much of it still remains (half-life is 30.17 years). Fallout levels peaked in 1963 and, with the ban on atmospheric tests, subsequently declined to minimal levels. Atmospheric-borne radionuclides accumulate near the soil surface, with ^{137}Cs concentrated within 30 cm of the surface (Wallbrink and Murray, 1996). General source areas of sediment can be identified based on variations in concentrations of bomb fallout and natural radionuclides. This tracer method is effective for distinguishing sediment derived from sheet and shallow rill erosion and sediment from gullies and stream channel walls because channel and gully walls deeper than 30 cm usually contain little or no ^{137}Cs. By comparing ^{137}Cs concentrations in stream sediment with concentrations in upland soils and channel banks, a simple mixing model (Wallbrink et al., 1996) can be used to quantify the proportion of stream sediment derived from upland or bank sources. The mixing model we used in this study was determined to be appropriate for distinguishing between bank and surface sources, as we have found that the vast majority of channel banks contain little or no ^{137}Cs.

An important issue in sediment source tracing is the choice of methods for sediment collection. Some studies of sediment tracers have drawn water samples from which suspended sediment was separated. Symader and Strunk (1992) described difficulties with use of suspended sediment to identify source areas. Principal problems are the varying levels of enrichment of suspended sediment in fines and in organic matter relative to the sources. Bottrill et al. (2000) contended that the use of recent floodplain deposits enable the contributions and long-term loading from individual sources to be assessed more reliably. The effective use of channel-bottom and low-floodplain sediment to distinguish between eroding surface soils and stream banks has been reported (Olley et al., 1993; Walling et al., 2003; Collins and Walling, 2007; Nagle et al., 2007), with Froelich and Walling (2005) using floodplain sediment without particle size corrections. Although it is difficult to find floodplain locations with deposition of fine sediment, especially in steeper, gravel bed channels, our previous work confirmed that ^{137}Cs concentrations in the silt and clay fraction (< 63 μm) of carefully collected channel-margin samples were similar to those collected from beaver ponds, behind dams, and from water treatment plant settling ponds (Nagle and Ritchie, 2004, Nagle et al., 2007). Another reason we used floodplain samples was that our older Ge dectectors needed a larger volume of sediment for analysis than can be obtained using suspended sediment samplers. Gellis et al. (2008) also described their difficulties in collecting enough sediment for radionuclide analyses using suspended sediment samplers.

Other studies have used radionuclides in suspended sediment to delineate source areas without taking any account of particle size differences between source areas and suspended sediment. Matisoff et al. (2002b) reported delineating the cultivated surface source of a plume of suspended sediment as it traveled 17 km down a drainage even without accounting in their calculations for particle-size changes during sediment entrainment and transport.

STUDY AREA

The 19,425 km^2 Upper Susquehanna River watershed lies within the Glaciated Appalachian Plateau (GAP) in south-central New York and northern Pennsylvania. The climate is temperate, with about 940 mm of precipitation distributed equally over the year (New York State Department of Environmental Conservation, 2004). Land cover in most of the Upper Susquehanna is forested uplands, with cultivated lands now concentrated primarily in large valleys on floodplains and on a few slopes with less acidic soils.

Land use within the Upper Susquehanna watershed has changed significantly since the late 19th century, when about 90% of the land was cleared for agriculture. Between 1970 and 1990, 1700 km^2 of agricultural lands were abandoned, with 90% of this reverting to forest (New York State Department of Environmental Conservation, 2004). Land cover in the Upper Susquehanna is now 64% forest and shrub lands, 9% cultivated, 20% pasture and hay, 6% urban/suburban, and 1% open water (Woodbury, 2008). The amount of land in urban/suburban land use has not changed in recent decades, with the urban impervious surface estimated at only about 0.66% (Upper Susquehanna Coalition, 2005). The glacial geology has been described (i.e., Denny and Lyford, 1963; Nelson, 1965). Detailed mapping of surficial glacial deposits has been done for small parts of the study area (Williams et al., 1909; Daugherty and Hanna, 1972), with less detailed mapping for the remainder (Denny and Lyford, 1963; Cadwell and Muller, 1986).

Surficial geology consists mostly of glacial till of variable texture and thickness, with less extensive glaciofluvial (outwash) deposits and small areas of glaciolacustrine sediments (Coates, 1971). Despite reports of significant declines in peak flow from small tributaries after reforestation (e.g., Schneider and Ayer, 1961), the Susquehanna headwaters are still one of the more flood-prone regions in the nation due to steep tributaries, relatively low infiltration rates in much of the compacted glacial till on hillsides, and many soils with a fragipan horizon that impedes drainage. In a 750 km^2 area in the central part of the study area, Coates (1963) found 82% of the soils to be relatively impervious. However, the vast portion of currently cropped lands is on gravelly valley bottom soils with high infiltration.

Forested hillsides in the Upper Susquehanna were cleared for relatively brief periods of cultivation on steeper lands before use as pasture and reversion of most hillside land to forest. Many farms in the Upper Susquehanna were dairy farms on steeper slopes with less productive, acidic soils (Gustafson et al., 1930), unlike the rich carbonate, grain-producing soils in southeastern Pennsylvania.

Compared to smaller tributaries, many of the largest channels appear relatively stable with high banks resulting from valley incision soon after glacial retreat (Skully and Arnold, 1981). Despite the Upper Susquehanna's tendency for flooding, analysis of channel changes from 1938 to 1985 at four locations along the mainstem of the upper Susquehanna (Bennett, 1989) indicated a very stable channel, even after events such as 1972 Hurricane Agnes. Nelson (1965) also reported that surveys along 22 km of the Chemung River, the principal western tributary of the upper Susquehanna, showed a stable channel with minimal erosion of banks.

METHODS

Field Sampling

In this study, the nuclear bomb–derived radionuclide ^{137}Cs was used as a tracer to quantify the sources of fluvial sediment in the study streams. For each study stream, recently deposited sediment samples were taken from channel margins and deposits immediately adjacent to the active channels inside the bankfull channel level. Such recent deposits were easily identified because they were usually saturated and had abundant organic materials such as leaf fragments (Fig. 1). Stream sediment samples were collected from 51 locations in 15 tributaries in the Upper Susquehanna basin (Fig. 2), where recent fine sediment deposition was obvious and public access was possible. We also took samples from two locations in Mill Creek, a very heavily cultivated watershed that is in glaciated terrain immediately south of our main study area because it had been identified as the location of an abandoned mill dam.

Potential sediment sources were sampled at locations in the watersheds. To characterize the most actively eroding banks, samples were collected from 33 stream banks in third- and fourth-order streams and large slumping streamside deposits 1.5

Fig. 1. Channel margin sediment sampling site.

m to 30 m in height by using a stainless steel trowel to scrape across 3 m^2 of the mid-portion of the bank. Actively eroding stream banks were identified in the field by recently exposed roots and sediment deposits at their base. Banks and stream-side slumps with well developed vegetation growing on them were not considered actively eroding.

To characterize upland soils, 256 cores were collected from 32 widely distributed sites using a 5 cm diameter corer to a depth of 10 cm. At each upland site, eight cores were collected at least 3 m apart and composited for analysis. Upland sites that were separately characterized for radionuclide concentrations included 22 in currently cropped agricultural fields, 5 in pastures, and 5 in forested areas. By compositing multiple samples spread over a site, the smaller-scale variability typically found in surface soils is accounted for (Nagle et al., 2000).

To assess the impacts of mill dams on sediment retention and later bank erosion, we examined historical maps and census data, visited many identified mill dam sites, and interviewed a U.S. Geological Survey hydrologist/ urban archaeologist familiar with our study area as well as a local informant whose grandfather owned one of the region's last working water mills. ^{14}C analyses of buried wood found in streambanks was done to date alluvium and identify locations with legacy sediments in the study streams and adjacent GAP region.

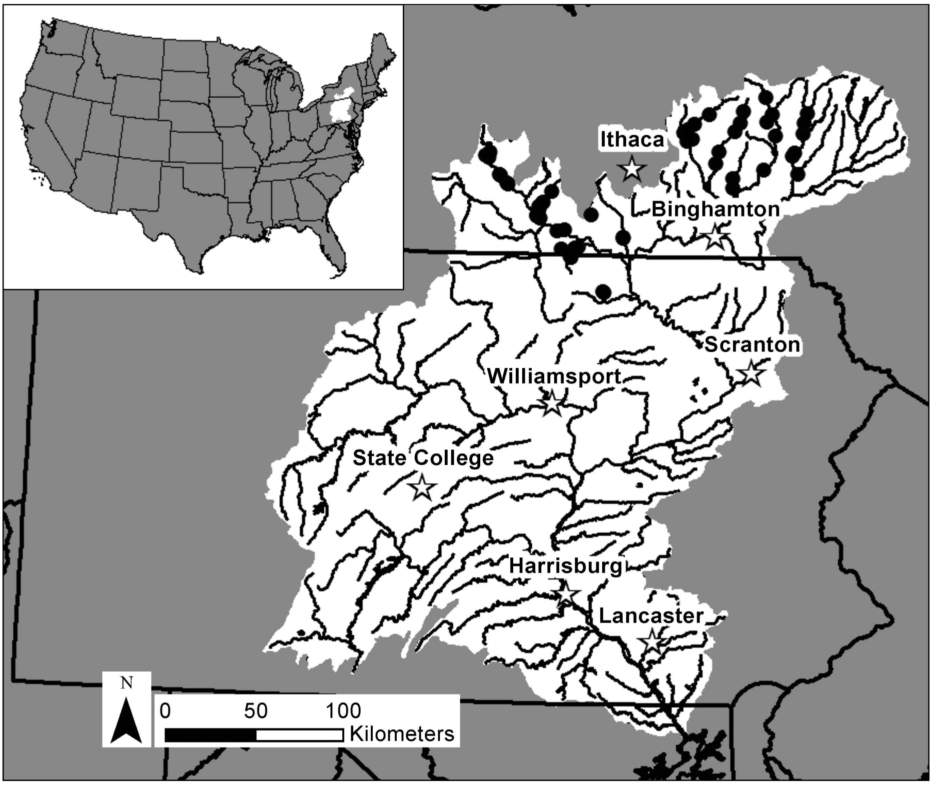

Fig. 2. Stream sediment sampling sites in the Upper Susquehanna basin. The inset map shows the location of the Upper Susquehanna basin (black) within the conterminous United States.

Laboratory Analysis

To minimize the influence of contrasts in particle-size composition between source materials and channel sediment on the values of the fingerprint properties, all measurements of tracer properties were undertaken on the <63 μm fraction (Walling et al., 1993; Walling, 2004). This size represents the break point between very fine sand and silt and the upper limit of most sediment reported to be carried as suspended loads. Samples were dried, lightly ground, and sieved to separate out the < 63 μm fraction. The sieved samples were analyzed for ^{137}Cs concentrations using Gamma-ray analysis at the USDA-Agricultural Research Service National Hydrology Lab in Beltsville, MD. Gamma-ray analyses were performed using the Canberra-2000 Genie-2000 Spectroscopy System. The system is calibrated and efficiency determined using an analytic mixed radionuclide standard (10 nuclides), the calibration of which can be traced to U.S. National Institute of Standards and Technology. The count time for each sample was 24 hours, providing a measurement precision of ±4 to 5% on most samples.

Data Analysis

To quantify the relative contributions of bank and cultivated sediment sources, data on ^{137}Cs concentration were analyzed with a mixing model (Wallbrink et al., 1996).

$$Cs = \frac{(Pr - Pb) \times 100}{(Ps - Pb)} \tag{1}$$

where Cs = contribution from cultivated surface sources (%), Pr = value of ^{137}Cs for stream sediment in mBq/g, Ps = value of ^{137}Cs for cultivated soil in mBq/g, and Pb = value of ^{137}Cs for bank material in mBq/g.

To account for uncertainty in the mixing model, we used quantitative uncertainty analysis, specifically a Monte Carlo approach. In this approach, model parameters are represented not as single values, such as the mean, but rather as statistical distributions of values. Samples are taken from these distributions and used in the model, and this process is repeated thousands of times to produce a large number of predicted values (Morgan and Henrion, 1990). The 50th percentile of this distribution of values of ^{137}Cs represents the median prediction, and other quantiles can be used as measures of dispersion of the predicted value.

For our analysis, distribution functions were fit to sample data for each of the parameters in Equation (1), and then values were selected from each distribution using Latin Hypercube sampling using @Risk and BestFit software (Version: Professional 4.5, Palisade Corporation, Ithaca, NY). The parameters were assumed to be independent of each other, and upland soil contributions to stream sediment were assumed to come from cultivated land, as erosion from forest and meadow in this have been reported to be minimal (Lamb et al, 1950; Patric et al. 1984). Separate analyses were conducted for each stream, and 100,000 iterations were performed for each analysis to produce numerically stable results.

For the two streams with more than five bank samples (Seeley and Meads), a distribution was fit to bank samples from just that stream. For the other streams, a distribution was fit to all bank samples from all streams. For all streams, a distribution was fit to all cultivated soil samples. The result of the uncertainty analysis for each stream is the percentage of sediment from stream banks versus cultivated land represented as a distribution of predicted values (Equation 1). For all streams, we present three percentiles of this distribution—the 20th, 50th, and 80th. Some streams had three or fewer stream sediment samples, and for these streams the results do not include any effect of uncertainty in the stream samples due to low sample size. However, the results still include the effects of uncertainty in the bank and cultivated sediment data.

RESULTS

Mean levels of ^{137}Cs were much higher for forest soil (21.48 mBq/g) than on cultivated lands (7.19 mBq/g) (Table 1), with little difference in ^{137}Cs concentrations between forests and pastures (21.12 mBq/g). Radionuclide levels on cultivated lands also showed the expected range of variability (3.56–11.36 mBq/g) that result from

Table 1. Comparison of Mean ^{137}Cs (mBq/g) Levels for Stream Sediment and Potential Source Materials in Upper Susquehanna Basin

	Stream bank material (n = 33)	Cultivated[a] surface soil (n = 22)	Pasture[a] surface soil (n = 5)	Forest[a] surface soil (n = 5)	Stream sediment (n = 53)
Cs-137 (mBq/g)	1.00	7.19	21.12	21.48	4.47
Range (mBq/g)	0–8.09	3.56–11.36	17.91–24.69	17.47-25.4	0–21.26

[a]Each surface sample was a composite of eight separate cores distributed across the study slopes.

impacts of erosion, cultivation, and deposition of eroded soil on lower slopes (Nagle et al., 2000). Past sampling in the region (Nagle et al., 2007) had showed ^{137}Cs levels of 10.25 mBq/g from cultivated lands, while those found during this sampling were lower. This difference may result from sample sites being on floodplains, where cultivated lands are concentrated and where occasional overbank flows deposit sediment that dilutes the surface ^{137}Cs concentrations in these fields.

Only 8 of the 33 bank samples had any ^{137}Cs present (0–8.09 mBq/g), with a mean of 1.00 mBq/g for all bank samples. The surfaces of most presently eroding banks were thus not exposed to atmospheric bomb fallout during the highest fallout years around 1960. These results for bank samples were similar to those (0.35 mBq/g, range = 0–4.7 mBq/g, corrected for radioactive decay) found in 26 banks sampled in a previous study in other areas of the GAP (Nagle et al., 2007). The main sources of variability in bank samples were a few sites with alluvium deposited since 1955 (Nagle and Ritchie, 1999). Seeley and lower Meads Creeks were unusual, with a few banks showing anomalously high ^{137}Cs levels. These may indicate recent overbank flood deposits or flood scouring and deposition of soil from adjacent floodplains.

Because we have found that most channel banks have little or no ^{137}Cs, the mixing model should be effective for distinguishing between bank and cultivated surface sources. Contributions of bank erosion to fine sediment loads in the 15 study tributaries basin ranged from 0 to 100% (Table 2), with a median contribution of 53%. Based on the quantitative uncertainty analysis, these estimates for source loadings are more precise for some streams than others. For example, for the Chenango River, with 44% bank erosion (Fig. 3), there is a 20% chance that the contribution of banks was as low as 6% or as high as 71%. However, estimates for Meads Creek, with 92% bank erosion, had a smaller range of 77–100% (Table 2).

In one stream, (Seeley Creek), high rates of bank erosion were also driven by severe floodplain alterations due to road construction that concentrated flows from a bifurcated channel into a single channel. Seeley Creek also has the largest eroding streamside bluffs of fine glacial material found in the entire study area. Meads Creek (92% from bank erosion) and its major tributary Dry Run (100% from bank erosion) also contain reaches with eroding bluffs of fine glacial material. Erosion of these bluffs and other high banks appears to be driven by deposition of coarse material on point bars that pushed the channels against the opposite banks.

Table 2. Concentration of Cs-137 (mBq g^{-1} in Sediment and Percentage of Fine Sediment from Surface Soils Based on Quantitative Uncertainty Analysis

Stream (stream order)	Cs-137 in stream margin sediment, mBq g^{-1}		Percentage of fine sediment from cultivated land surface erosion			Percentage of fine sediment from bank erosion
	Mean	Range	Low (20th percentile)[b]	Median (50th percentile)	High (80th percentile)	Median (50th percentile)
Unadilla (4th)	3.87 (n = 6)	1.96–5.9	23	46	80	54
Meads (4th)	1.56 (n = 7)	0.63–2.29	0	8	23	92
East Fork Tioughnioga (4th)	4.44 (n = 4)	2.76–6.38	34	56	93	44
Seeley (4th)	3.45 (n = 7)	0–5.38	5	40	87	60
Cohocton (4th)	6.12 (n = 7)	1.94–12.4	37	75	100	25
Otselic (4th)	5.45 (n = 5)	1.97–8.29	33	68	100	32
Chenango (4th)	4.34 (n = 4)	2.67–6.15	29	56	94	44
Trout (4th)	3.80 (n = 3)	3.5–4.28	*31* [a]	47	*72* [a]	53
Cayuta (3rd)	2.30 (n = 2)	1.96–2.63	*11* [a]	23	*38* [a]	77
Genegantslet (4th)	20.61 (n = 2)	19.96–21.26	*100*[a]	100[b]	*100*[a]	0
Mill Creek (3rd)	0.00 (n = 2)	0–0	*0* [a]	0	*0* [a]	100
Pleasant Brook (3rd)	5.59 (n = 1)	–	*54* [a]	77	*100* [a]	23
Dry Run (3rd)	0.00 (n = 1)	–	*0* [a]	0	*0* [a]	100
North Bulkley (3rd)	1.07 (n = 1)	–	*0* [a]	6	*13* [a]	94
Mudlick Creek (3rd)	5.84 (n = 1)	–	*57* [a]	81	*100* [a]	19

[a]Values in italic font for 20th and 80th percentile estimates include uncertainty in bank and cultivated sediment data, but not uncertainty in stream sediment data due to low sample size; see text for details.
[b]High ^{137}Cs levels indicate that fine sediment in Genegantslet Creek is from pasture or forest lands.

Fig. 3. Stable banks along the upper Chenago River.

Eight of the study tributaries had over half of fine sediments derived from channel banks. Genegantslet Creek showed anomalous results since the sediment had ^{137}Cs levels of 19.96–21.26 mBq/g, indicating that forest or pasture surfaces were the sources rather than cultivated lands. The sediment was likely delivered from marshy floodplains upstream of the sampling sites. In the 14 other streams, cultivated lands accounted for an average of 42% of the fine sediment (median is 47 %).

In one high bank-sediment stream (Mill Creek, 100% bank sediment, Table 2), the reach with the most serious bank erosion in the tributary was reported (Lovegreen, pers. commun., 2006) as the location of a mill dam in the 19th century. However, a major channel reconstruction project at this site may have put much fine sediment into the stream, which may also explain the unusually high contribution of bank sediment. With the exception of this tributary, the impacts of mill dams on bank erosion appears to be relatively minor in our study area compared to reports from parts of the Lower Susquehanna (Walter and Merrits, 2008).

DISCUSSION

In tracer studies, there are several potential sources of uncertainty in the estimates of sediment sources. We have addressed important uncertainties by using quantitative uncertainty analysis. As expected, when fewer samples are collected, or there is much variation among samples from the same source area, there is more uncertainty in predictions of the amount of sediment from banks versus cultivated lands (Table 2). However, not all potential sources of uncertainty were included in our model. No analysis of particle sizes was performed in this study, but, as has been standard procedure in tracer studies, all samples were sieved to separate out the <63 μm fraction (silts and clays) for analysis. Also, we avoided the problems with particle-size enrichment that can occur when using suspended sediment by using samples from channel margins.

In a previous study of sediment sources in central New York, we observed higher proportions of bank sediments in catchments with streamside glaciolacustrine deposits, and attributed the high bank sediment yields in these streams to channels eroding these fine-textured sediments (Nagle et al., 2007). In the GAP, north-flowing rivers often contain more glaciolacustine deposits because lacustrine silt and clay were deposited as proglacial meltwaters ponded in streams flowing north to the ice front during recession of the glaciers. However, as the ice margin retreated from south-flowing basins, fewer lakes formed and silts and clays were flushed from valley fill, leaving a higher percentage of sand and gravel in the lag outwash deposits. This process resulted in cleaner, coarser, and more permeable valley fill in south-flowing rivers (Coates, 1971, 1974). Thirteen of our study tributaries in the Upper Susquehanna were south-flowing, with limited streamside glaciolacustrine deposits (Cadwell and Muller, 1986). Of the sites used, only north-flowing Seeley Creek has prominent eroding glaciolacustrine deposits (Fig. 4).

Legacy impacts of agricultural land use on streams can persist even decades after reversion of most of a watershed to forest (Harding et al., 1998). Agricultural clearing of the Upper Susquehanna in the early to mid-19th century appears to have resulted in the extension of some first-order tributaries into coarse glacial debris, such that channel incision and widening mobilized coarse materials. Mobilization of gravels and cobbles can send coarse sediment pulses migrating downstream in moving zones of channel instability and bank erosion that can persist for decades (Kondolf et al., 2002). Fitzpatrick and others (1999) estimated that bankfull flows in glaciated North Fish Creek, Wisconsin, increased threefold after agricultural clearing in the late 19th century. Knox (1977) estimated a similar two- to four-fold increase in bankfull flows in other Wisconsin streams. Transportation and deposition of bedload sediment accompanied by bank erosion resulted in channel widening. Raw, eroding banks from widened channels in coarse deposits are often found along small, forested channels draining agricultural lands in our study area (Fig. 5). In the only study of contemporary coarse sediment generation in the glaciated Appalachian Plateau, Renwick (1976) described debris flows in a steep channel draining from cultivated lands through a bluff of glacial sand and gravel. In his study, 500 m^3 of coarse material were removed from the 150 m channel in a single storm.

The Impact of Mill Dams and Legacy Sediment on Bank Erosion

An important reason for the much greater impacts of mill dams in the Lower Susquehanna compared to our study area is that dams in the lower river were larger and sturdier. The 1840 census (U.S. Census Bureau, 1841) showed that, in Lancaster County, PA, 71% of the 369 mills were flour or grist mills, with the rest sawmills.

Fig. 4. Eroding glacial banks, Seeley Creek.

But in Tioga County, NY, the county with the largest number of mills in the Upper Susquehanna, 85% of the 303 mills in 1840 were sawmills, which were often farm mills on small tributaries that carried enough flow only seasonally to run the mills.

Construction of large, stable dams capable of holding quantities of sediment over centuries was more difficult in the northern Susquehanna basin, compared to southeastern Pennsylvania, due to a lack of suitable rock for construction in areas dominated by shale. Steep tributaries and waterfalls in this region also allowed settlers to use flumes and avoid building mill dams. Sediment deposition was observed at a few documented mill dam sites, and an eroding bank in Mill Creek in northern Pennsylvania was identified as an old mill dam site. But examination of locations in Tompkins County and many locations in northern Tioga County, NY, mapped in the 1860s (Stone and Stewart, 1866; Beers, 1975) as having mill dams and ponds, showed no eroding banks and no clear evidence of sediment deposition like that documented in southeastern Pennsylvania by Walter and Merritts (2008).

Many of the mill dams were in-stream structures near existing waterfalls, with most of the diverted water either "run of the river," or run through the mills after minimal pooling of water. The dams were small, usually constructed of wood and prone to failure. Most of the dams were removed by floods, and most sediments behind them washed downstream. In 1832 and 1835, floods washed out most of the dams in the region (Kappel, pers. commun., 2008).

Fig. 5. First-order tributary eroding through glacial moraine.

In contrast to the clearly important role of sediments stored at mill dam sites in the southern Susquehanna basin (Walter and Merritts, 2008), our study streams accumulated much less legacy sediment, and most of the eroding alluvial material predates settlement. Less alluvial accumulation of eroded agricultural soils may be due to the lower erodibility of soils in rocky, glaciated regions (Gordon, 1979; Meade, 1982), lower rainfall erosivity (Trimble, pers. commun., 2007), and less intensive cropping, with more land in pasture and forest compared to the Lower Susquehanna.

The alluvial materials through which most of the streams in our study area were cutting did not represent legacy sediments derived following forest clearing and settlement by Europeans. The ^{14}C ages of buried wood that we collected in alluvial sediments at 11 locations across the GAP ranged from 140 to 7380 yr, with a median age of 680 yr (mean is 1298 years). Most streams were cutting primarily through much older alluvial material that predated Euro-American settlement, although in a few locations, buried A horizons were found under about 50 cm of lighter colored alluvial material, which was probably post-settlement deposition. Two GAP locations identified by ^{14}C analysis as having deep deposits (150 cm) of post-settlement legacy sediments were very similar to those reported from many sites in southeastern Pennsylvania (Walter and Merritts, 2008), with buried hydric soils containing much organic material characteristically found below the legacy sediment, indicating low-gradient streams in valley locations where deposition was likely. However, 1866 maps did not show mill dams at these locations (Stone and Stewart, 1866).

Land clearing and cultivation began in the Upper Susquehanna about a century later than in southeastern Pennsylvania, with cultivated land peaking around 1880 (Whitney, 1994). Intensive settlement of the region came after 1800, with much of the early economy depending on logging and with a shift to agriculture only after 1835 in some areas (Kensler and Melvin, 1930). This explains the large number of water-driven sawmills in 1840.

Erosion and Sediment Yields in the Upper Susquehanna

We do not suggest that sediment from pasture or forested lands does not enter the channel, but previous studies in our study area have shown contributions from those sources to be minimal. In an early study of soil erosion plots, Lamb at al. (1950) reported that sod meadow generated only 0.017 t ha^{-1} yr^{-1}, and yields from forest land plots were almost undetectable. Forest land erosion reported by Patric et al. (1984) for 291 sites in eastern forests ranged from 0.02 to 4.37 t ha^{-1} yr^{-1}, with a mean of 0.3 t ha^{-1} yr^{1}, even though most of these forests were managed with road networks and logging.

The likelihood of a low contribution of agricultural fields to fine sediment loads in many of our study streams is corroborated by other erosion studies in the region (Lamb and Chapman, 1943; Lamb et al. 1944; Reed, 1972). In the most intensive, small watershed study of erosion and sediment sources in the Upper Susquehanna, Reed (1972) compared sediment yields over a 13-year period (1954–1967) in two small treatment and control watersheds with typical rural land uses in the upper Tioga River drainage. Land in the 26 km^2 treatment watershed was 54% grassland, 40% forest, and 6% cultivated. Adoption of extensive soil conservation measures in the treated watershed reduced sediment yields by 47% during the growing season, but not during the winter or during large summer storm events, when 96% of total sediment was transported. The continued high sediment load was explained by export of stored sediment in gullies and by channel erosion.

In the earliest study of small agricultural erosion plots in the glaciated Upper Susquehanna, Lamb et al. (1944) reported erosion rates, based on eight years of field data, of only 3.9 and 5.8 t ha^{-1} yr^{-1} on 9% and 20% slopes, respectively. Such small plot studies overestimate sediment delivery to streams because most eroded soil accumulates as colluvium on lower slopes (de Ploey and Yair, 1985; Walling and Collins, 2008). Erosion from plots on weedy idle crop lands was 0.44 t ha^{-1} yr^{-1} (Lamb et al., 1950). These relatively low agricultural erosion rates on even 20% slopes might be explained by the ubiquitous stones in many agricultural soils of glaciated regions (Gordon, 1979). Removing all stones over 5 cm diameter from field plots resulted in a 220% increase in erosion rates (Lamb and Chapman, 1943).

In contrast to relatively low agricultural erosion reported in the glaciated Upper Susquehanna, Gellis et al. (2008) used the ^{137}Cs method to calculate much higher contemporary net erosion rates in the lower Susquehanna's Conestoga watershed, with an average of 19.4 t ha^{-1} yr^{-1} measured from five cultivated fields on 0–8% slopes.

With the abandonment of much steep croplands since 1900, agricultural erosion has decreased. This may account for the relative importance of bank sediment in some tributaries. Current sediment loads in many streams of the Upper Susquehanna are not high compared to those in New York state (Nagle et al., 2007) or the rest of the Susquehanna basin, with some major tributaries showing low yields (Table 3), although the data presented should be viewed with caution due to brief periods of measurement for many streams. Sediment yields reported by Williams and Reed (1972) in the eastern Upper Susquehanna basin were generally lower than those in the western basin (Table 3), which they explained was due to the presence of coarser sandstone bedrock in the east, with minimal deposits of eroding fine-grained glacial drift and lacustrine deposits derived from shale. Short-term studies reported by Williams and Reed (1972) in eastern tributaries, such as the Unadilla and Chenango, show anomalously low yields of 14 and 17 t km^{-2} yr^{-1}, even lower than those assumed for minimally disturbed forested watersheds in the Northeast (Kunkle and Comer, 1972; Williams and Reed, 1972) (Table 3). The western Upper Susquehanna's highest yields, at 154 t km^{-2} yr^{-1}, are in the Canisteo River (Williams and Reed, 1972), where erosive muck soils were ditched and drained for agriculture and areas of severe bank erosion exist in its headwaters.

An explanation for the striking lack of correlation between the percentage of agricultural land and basin sediment yields from the upper Susquehanna, compared to those of unglaciated river basins in the Atlantic drainage of the U.S. (Meade, 1982), is that rock armors the soil of glaciated regions against erosion (Gordon, 1979). Lower export of eroded agricultural soils might also be due to relatively low rainfall erosivity compared to other regions on the Atlantic seaboard (Meade, 1982) and lower sediment export from drainage networks interrupted by many lakes and bogs left as the continental ice sheets retreated at the end of the Wisconsin glacial period (Bloom, 2008).

CONCLUSIONS

To determine the proportion of stream sediment that eroded from banks, we compared the concentrations of the nuclear bomb–derived radionuclide ^{137}Cs in fluvial sediment samples from stream banks and cultivated lands in the glaciated Upper Susquehanna basin. Our use of recently deposited channel margin sediment from inside the bankfull channel was effective, although we caution others before attempting this approach because finding sites with recent deposition of very fine sediment is difficult in many tributaries. The simple mixing model was effective for distinguishing between bank and cultivated sources, since we have found that most channel banks in the area have little or no ^{137}Cs.

The contributions of bank sediment to stream sediment in the 15 study streams ranged from 0 to 100%, with a median contribution of 53%. In eight of the study tributaries, over half of the deposited sediments were derived from channel banks. Mill Creek had a 100% contribution from bank erosion, with an entrenched channel and eroding banks at an identified mill dam site. A channel reconstruction project on this site may also account for the high percentage of sediment from bank erosion. With the exception of this site, the impacts of abandoned mill dams in our study area were relatively minor compared to reports from the southern Susquehanna (Walter and Merritts, 2008). We suggest that bank erosion in many smaller tributaries in the

Table 3. Suspended Sediment Yields for Upper Susquehanna and Other Streams in the Northeast (in t km^{-2} yr^{-1})

Source	Location	t km^{-2} yr^{-1}
Minimally disturbed watersheds in Northeast U.S.		
Kunkle and Comer (1972)	Vermont Sleepers watersheds (glaciated, forested and minimally disturbed)	22–52
USGS Susquehanna study (Williams and Reed, 1972)	Driftwood Creek (non-glaciated, forested and minimally disturbed, mid- Susquehanna)	23
Sediment Yields from Upper and Lower Susquehanna		
Gellis et al. (2006)	Susquehanna River (mean for 36 stations, 1952–2001)	87
	Conestoga River (southeast PA, Piedmont, mean of 4 stations, 1985–2001)	279
	Little Conestoga Creek (southeast PA, piedmont, 1985–1992)	827
Reed (1972)	Corey Creek (Upper Susquehanna,Tioga River drainage, 1954–1967)	44
USGS Susquehanna study (Williams and Reed, 1972); stations from 1962 to 1967, all less than three years of data	Tioga River at Erwins (western Upper Susquehanna)	66
	Chemung (western Upper Susquehanna)	53
	Canisteo River (western Upper Susquehanna)	154
	Unadilla River (eastern Upper Susquehanna)	14
	Chenango River (eastern Upper Susquehanna)	17
	Owego at Owego (eastern Upper Susquehanna)	24
	Susquehanna at Conklin (eastern Upper Susquehanna)	28
Gellis et al. (2004)	Susquehanna at Towanda, 1985–1996 estimated	36
	Tioga at Lindley , NY; 1975–1980 (western Upper Susquehanna)	141
	Chemung at Chemung, 1975–1977 (western Upper Susquehanna)	115

Upper Susquehanna is a legacy impact from early Euro-American settlement, with mobilization of coarse glacial materials driving channel widening and instability.

Most streams in the western Upper Susquehanna study area had much higher levels of bank erosion than in the eastern region. The seven streams in the western region averaged 67% bank sediment (median 77%). The seven eastern streams averaged 36% bank sediment (median 44%). Large actively eroding banks and fine-grained streamside glacial deposits are much less common in the eastern than the western area.

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REFERENCES

Beers, F. W. (1975) *Atlas of Tioga Co New York: From Actual Surveys* (reprint of the 1869 edition). Churchville, NY. Last accessed April 8, 2012 from http://tcpl.org/local-history/books-maps.php

Bennett, S. J. (1989) An example of channel stability: The Susquehanna River in eastern New York state. *Northeastern Geology,* Vol. 11, 29–39.

Bloom, A.L. (2008) The Late Pleistocene glacial history and environment of New York state mastodons. In W. D. Allmon and P. L. Nester, eds., *Mastodon Paleobiology, Taphonomy, and Paleoenvironment in the Late Pleistocene New York State: Studies on Hyde Park, Chemung and North Java Sites*. *Palaeontographica Americana*, Vol. 61, 13–23.

Boomer, K. B., Weller, D. E., and Jordon, T. E. (2008) Empirical models based on the Universal Soil Loss Equation fail to predict sediment discharges from Chesapeake Bay catchments. *Journal of Environmental Quality,* Vol. 37, 79–89.

Bottrill, L. J., Walling, D. E., and Leeks, G. J. L. (2000) Using recent overbank deposits to investigate contemporary sediment sources in larger river basins. In I. D. L. Foster, ed., *Tracers in Geomorphology*. New York, NY: John Wiley, 369–386.

Brigham, M. E., McCollough, C. J., and Wilkinson, P. (2001) *Analysis of Suspended Sediment Concentrations and Radioisotope levels in the Wild Rice River Basin, Northwestern Minnesota, 1973–98*. Washington, DC: U.S. Geological Survey, Water Resources Investigation Report 01-4192.

Cadwell, D. H. and Muller, E. H. (1986) *Surficial Geologic Map of New York*. Albany, NY: New York State Museum–Geological Survey.

Campo, S. H. and Desloges, J. R. (1994) Sediment yield conditioned by glaciation in a rural agricultural basin of southern Ontario, Canada. *Physical Geography*, Vol. 15, 495–515.

Coates, D. R. (1963) Geomorphology of the Binghamton area. In D. R. Coates, ed., *Geology of South-Central New York. New York State Geological Association, 35th Annual Meeting, Binghamton, New York, May 3–4, 1963*. Binghamton, NY: New York State Geological Association, 97–113.

Coates, D. R. (1971) Hydrogeomorphology of Susquehanna and Delaware basins. In M. Morisawa, ed., *Quantitative Geomorphology: Some Aspects and Applications*. Binghamton, NY: State University of New York, 273–306.

Coates, D. R. (1974) Reappraisal of the glaciated Appalachian Plateau. In D. R. Coates, ed., *Glacial Geomorphology.* Binghamton, NY: State University of New York, 205–244.

Collins, A. L. and Walling, D. E. (2004) Documenting catchment suspended sediment sources: Problems, approaches, and prospects. *Progress in Physical Geography*, Vol. 28, 159–196.

Collins, A. L. and Walling, D. E. (2007) The storage and provenance of fine sediment on the channel bed of contrasting lowland permeable catchments, UK. *River Research and Applications,* Vol. 23, 429–450.

Daugherty, L.-R. A. and Hanna, W. E. (1972) Landscape Evolution of a Glaciated Upland Valley in South-Central New York. Unpubl. Master's thesis, Cornell University (OCLC 63880863).

Davis, C. M. and Fox, J. F. (2009) Sediment fingerprinting: Review of the method and future improvements for allocating nonpoint source pollution. *Journal of Environmental Engineering*, Vol 135, 490–504.

Denny, C. S. and Lyford, W. H. (1963) *Surficial Geology and Soils of the Elmira-Williamsport Region, New York and Pennsylvania*. Washington, DC: U.S. Geological Survey Professional Paper 379.

de Ploey, J. and Yair, A. (1985) Promoted erosion and controlled colluviation: A proposal concerning land management and landscape evolution. *Catena,* Vol. 12, 105–110.

Devereux, O. H., Prestegaard, K. L., Needleman, B. A., and Gellis, A. C. (2010) Suspended sediment sources in an urban watershed, Northeast Branch Anacostia River, Maryland. *Hydrological Processes*. Vol. 24, 1391–1403.

Fitzpatrick, F. A., Knox, J. C., and Whitman, H. E. (1999) *Effects of Historical Land-Cover Changes on Flooding and Sedimentation, North Fish Creek, Wisconsin*. Middleton, WI: USGS Water Investigations Report 99-4083.

Foster, I. D. L. and Lees, J. A. (2000) Tracers in geomorphology: Theory and applications in tracing fine particulate sediments. In I. D. L. Foster, ed., *Tracers in Geomorphology*. London, UK: John Wiley and Sons, 3–20.

Fox, J. F. (2009) Identification of sediment sources in forested watersheds with surface coal mining disturbance using carbon and nitrogen isotopes. *Journal of American Water Resources Association*, Vol 45, 1273–1289.

Froehlich, W. and Walling, D. E. (2005) Using environmental radionuclides to elucidate sediment sources within a small drainage basin in the Polish Flysch Carpathians. In D. E. Walling and A. J. Horowitz , eds., *Sediment Budgets 1*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publ. No. 291, 102–112.

Gellis, A. C., Banks, W. S., Langland, M. J., and Martucci, S. K. (2004) *Summary of Suspended Sediment Data for Streams Draining the Chesapeake Bay Watershed, Water Years 1952–2002*. Washington, DC: U.S. Geological Survey, Scientific Investigations Report 2004-5056.

Gellis, A. C., Hupp, C. R., Pavich, M. J., Landwehr, J. M., Banks, W. S. L., Hubbard, B. E., Langland, M. J., Ritchie, J. C., and Reuter, J. M. (2008) *Sources, Transport, and Storage of Sediment at Selected Sites in the Chesapeake Bay Watershed*. Washington, DC: U.S. Geological Survey Scientific Investigations Report 2008-5186.

Gellis, A. C., Pavich, M. J., Banks, W. S., Langland, M. J., and Landwehr, J. M. (2006) Suspended sediment yields in the Chesapeake Bay watershed (1952–2001). In *Geological Society of America. Northeastern Section 41st Annual Meeting, Abstracts with Programs*, 85.

Glasman, J. R. (1997) *Clay Minerology of Soils Exposed in Riverbank Cuts Below Big Cliff Reservoir, North Santiam River Drainage*. Philomath, OR: Willamette Geological Service.

Gordon, R. B. (1979) Denudation rate of central New England determined from estuarine sedimentation. *American Journal of Science,* Vol. 279, 632–642.

Gustafson, A. F., Buckman, H. O., and Cooper, H. P. (1930) *Soil and Field Crop Management for Chenango County, New York*. Ithaca, NY: Cornell Agricultural Experiment Station, Bulletin 514.

Harding, J. S., Benfield, E. F., Bolstad, P. V., Helfman, G. S., and Jones, E. B. D. (1998) Stream biodiversity: The ghost of land use past. *Proceedings of the National Academy of Sciences,* Vol. 95, 14,843–14,847.

Hasholt, P. (1988) On identification of sources of sediment transport in small basins with special reference to particulate phosphorus. In M.P. Bordas and D.E. Walling, eds., *Sediment Budgets*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publication. No. 174, 241–250.

Juracek, K. E. and Ziegler, C. (2009) Estimation of sediment sources using selected chemical tracers in the Perry Lake basin, Kansas, USA. *Journal of Sediment Research*, Vol. 24, 108–125.

Kappel, W. (2008) Personal commun. U.S. Geological Survey, Ithaca NY, March 12.

Kensler, G. M. and Melvin, B. L. (1930) *A Partial Sociological Study of Dryden, New York, with Special Emphasis on its Historical Development*. Ithaca, NY: Cornell University Agricultural Experiment Station, Bulletin 504.

Knox, J. C. (1977) Human impacts on Wisconsin stream channels. *Annals of the Association of American Geographers,* Vol. 67, 323–342.

Kondolf, G. M., Piegay, H., and Landon, N. (2002) Channel response to increased and decreased bedload supply from land use change: Contrasts between two catchments. *Geomorphology,* Vol. 45, 35–51.

Kunkle, S. H. and Comer, G. H. (1972) *Suspended, Bed and Dissolved Sediment Loads in the Sleepers River, Vermont*. Washington, DC: U.S. Department of Agriculture Research Service, Publ. ARS41-188.

Lamb, J. and Chapman, J. E. (1943) Effect of surface stones on erosion, evaporation, soil temperature and soil moisture. *Journal of American Society of Agronomy,* Vol. 35, 567–578.

Lamb, J., Andrews, J. S., and Gustafson, A. F. (1944) *Experiments in the Control of Soil Erosion in Southern New York*. Ithaca, NY: Cornell University Agricultural Experimental Station, Bulletin 811.

Lamb, J., Carlton E. A., and Free, G. R. (1950) Effect of past management and erosion of soil on fertilizer efficiency. *Soil Science*, Vol. 5, 385–392.

Lovegreen, M. (2006) Personal communication. Bradford County Soil and Water Conservation District, Towanda, PA, September 21.

Matisoff, G., Bonniwell, E. C., and Whiting, P. J. (2002a) Radionuclides as indicators of sediment transport in agricultural watersheds that drain to Lake Erie. *Journal of Environmental Quality,* Vol. 31, 62–72.

Matisoff, G., Bonniwell, E. C., and Whiting P. J. (2002b) Soil erosion and sediment sources in an Ohio watershed using Beryllium-7, Cesium-137, and Lead-210. *Journal of Environmental Quality*, Vol. 31, 54–61.

Meade, R. H. (1982) Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. *Journal of Geology,* Vol. 90, 235–252.

Morgan, M. G. and Henrion, M. (1990) *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. New York, NY: Cambridge University Press.

Nagle, G. N., Fahey, T. J., Ritchie, J., and Woodbury, P. B. (2007) Variations in sediment sources and yields in the Finger Lakes and Catskills regions of New York. *Hydrological Processes,* Vol. 21, 828–838.

Nagle, G. N., Lassoie, J. P., and Fahey, T. J. (2000) The use of caesium-137 to estimate agricultural erosion on steep slopes in a tropical watershed. *Hydrological Processes,* Vol. 14, 957–969.

Nagle, G. N. and Ritchie, J. (1999) The use of tracers to study sediment sources in three streams in northeastern Oregon. *Physical Geography*, Vol. 20, 348–366.

Nagle, G. N. and Ritchie, J. (2004) Wheat field erosion rates and channel bottom sediment sources in an intensively cropped northeastern Oregon drainage basin. *Land Degradation and Development,* Vol. 14, 1–12.

Nelson, J. G. (1965) Some effects of glaciation on the Susquehanna River valley. *Annals of the Association of American Geographers,* Vol. 55, 404–448.

New York State Department of Environmental Conservation (2004) *New York State Watershed Restoration and Protection Action Strategy: Susquehanna and Chemung River Basins*. Albany, NY: New York State Department of Environmental Conservation.

Odgaard, A. J. (1987), Streambank erosion along two rivers in Iowa. *Water Resources Research*, Vol. 23, 1225–1236.

Olley, J. M., Murray, A. S., Mackenzie, D. H., and Edwards, K. (1993) Identifying sediment sources in a gullied catchment using natural and anthropogenic radioactivity. *Water Resources Research,* Vol. 29, 1037–1043.

Owens, P. N. and Walling, D. E. (2002) Changes in sediment sources and floodplain deposition rates in the catchment of the River Tweed, Scotland, over the last 100 years: The impact of climate and land use change. *Earth Surface Processes and Landforms,* Vol. 27, 403–423.

Patric, J. H., Evans, J. O. and Helvey, J. D. (1984) Summary of sediment yield data from forested lands in the United States. *Journal of Forestry*, Vol. 82, 101–104.

Peart, M. R. and Walling, D. E. (1986) Fingerprinting sediment sources: The example of a drainage basin in Devon, UK. In R.F. Hadley, ed., *Drainage Basin Sediment Delivery*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publ. No. 159, 41–55.

Peart, M. R. and Walling, D. E. (1988) Techniques for establishing suspended sediment sources in two drainage basins in Devon, UK: A comparative assessment. In M. P. Bordas and D. E. Walling, eds., *Sediment Budgets*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publ. No. 174, 269–279.

Phillips, J. D. (1991) Fluvial sediment budgets in the North Carolina piedmont. *Geomorphology,* Vol. 4, 231–241.

Reed, L. A. (1972) *Hydrology and Sedimentation of Corey Creek and Elk Run Basins: North Central Pennsylvania*. Washington, DC: U.S. Geological Survey Water Supply Paper1532-E.

Riedel, M. S., Verry, E. S., and Brooks, K. N. (2005) Impacts of land use conversion on bankfull discharge and mass wasting. *Journal of Environmental Management,* Vol. 76, 326–337.

Renwick, W. H. (1977) Erosion caused by intense rainfall in a small catchment in New York state. *Geology,* Vol. 5, 361–364.

Schneider, W. J. and Ayer, G. R. (1961) *Effect of Reforestation on Streamflow in Central New York*. Washington, DC: U.S. Geological Water Supply Paper 1602.

Sekely, A. C., Mulla, D. J., and Bauer, D. W. (2002) Streambank slumping and its contribution to the phosphorus and suspended sediment loads of the Blue Earth River, Minnesota. *Journal of Soil and Water Conservation,* Vol. 57, 243–250.

Scully, R. W. and Arnold, R. W. (1981) Halocene alluvial stratigraphy in the Upper Susquehanna River basin, New York. *Quaternary Research*, Vol. 15, 327–344.

Slattery, M. C., Burt, T. P., and Walden, J. (1995) The application of mineral magnetic measurements to quantify within-storm variations in suspended sediment sources. In C. Leibundgut, ed., *Tracer Technologies for Hydrological Systems*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publ. No. 229, 143–151.

Stone and Stewart (1866) *New Topographical Atlas of Tompkins County New York*. Philadelphia, PA: Stone and Stewart Publishers.

Symader, W. and Strunk, N. (1992) Determining the source of suspended particulate material. In D. E. Walling, T. R.Davies, and B. Hasholt, eds., *Erosion, Debris Flows, and Environment in Mountain Regions*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publ. No. 209, 177–185.

Trimble, S. W. (1983) A sediment budget for Coon Creek Basin in the Driftless Area, Wisconsin, 1853–1977. *American Journal of Science,* Vol. 283, 545–574.

Trimble, S. W. (2007) Personal communication. University of California, Los Angeles, Department of Geography, February 8.

Trimble, S. W. and Crosson, P. (2000) U.S. soil erosion rates: Myth and reality. *Science*, Vol. 289, 248–250.

Upper Susquehanna Coalition (2005) *New York State's Strategy to Address Nutrient and Sediment Problems in the Chesapeake Bay*. Burdett, NY: Upper Susquehanna Coalition.

Upper Susquehanna Coalition (2006) *Chesapeake Bay and New York State: Water Quality and Potential for Future Regulations*. Burdett, NY: Upper Susquehanna Coalition.

U.S. Census Bureau (1841) *Compendium of the Sixth Census, Recapitulation of the Aggregate Value and Produce, and Number of Persons Employed in Mines, Agriculture, Commerce, Manufactures by Counties*. Washington DC. U.S. Census Bureau.

Wallbrink, P. J. and Murray, A. S. (1996) Distribution and variability of Be-7 in soils under different surface cover conditions and its potential for describing soil redistribution processes. *Water Resources Research,* Vol. 32, 467–476.

Wallbrink, P. J., Murray, A. S., and Olley, J. M. (1998) Determining sources and residence time of suspended sediment in the Murrumbidgee River, New South Wales, Australia, using fallout -137 and Pb-210. *Water Resources Research,* Vol. 34, 879–887.

Wallbrink, P. J., Olley, J. M., Murray, A. S., and Olive, L. J. (1996) The contribution of subsoil to sediment yield in the Murrumbridgee River basin, New South Wales, Australia. In D. E. Walling and B. Webb, eds., *Erosion and Sediment Yield: Global and Regional Perspectives*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publ. No. 236, 347–355.

Walling, D. E. (2004) Using environmental radionuclides as tracers in sediment budget investigations. In J. Bogen, T. Fergus, and D. Walling, eds., *Erosion and Sediment Transport Measurement in Rivers: Technological and Methodological Advances*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publ. No. 283, 57–78.

Walling, D. E. and Collins, A. L. (2008) The catchment sediment budget as management tool. *Environmental Science and Policy,* Vol. 11, 136–143.

Walling, D. E., Collins, A. L., and McMellin, G. K. (2003) A reconnaissance survey of the source of interstitial fine sediment recovered from salmonid spawning gravels in England and Wales. *Hydrobiologia,* Vol. 497, 91–108.

Walling, D. E., Woodward, J. C., and Nicholas, A. P. (1993) A multi-parameter approach to fingerprinting suspended-sediment sources. In N. E. Peters, ed., *Tracers in Hydrology*. Wallingford, UK: International Association of Hydrological Sciences, IAHS Publ. No. 215, 329–338.

Walter, R. C. and Merritts, D. J. (2008) Natural streams and the legacy of water-powered mills. *Science,* Vol. 319, 299–304.

Whiting, P. J., Matisoff, G., Fornes, W., and Soster, F. M. (2005) Suspended sediment sources and transport distances in the Yellowstone River basin. *Geological Society of America Bulletin,* Vol. 117, 515–529.

Whitney, G. G. (1994) *From Coastal Wilderness to Fruited Plain: A History of Environmental Change in Temperate North America, 1500 to the Present*. Cambridge, UK. Cambridge University Press.

Williams, H. S., Tarr, R. S., and Kindle, E. M. (1909) *Watkins Glen–Catatonk Folio*. Washington, DC: U.S. Geological Survey.

Williams, K. F. and Reed, L. A. (1972) *Appraisal of Stream Sedimentation in the Susquehanna River Basin*. Washington, DC: U.S. Geological Survey Water-Supply Paper 1532-F.

Woodbury, P. (2008) *Assessment of 2001 National Land Cover Data Base*. Ithaca, NY: Cornell University.

Youngberg, C. T. and Klingeman, P. C. (1971) *Hills Creek Reservoir Turbidity Study*. Corvallis, OR: Oregon State University, Water Resources Research Institute.

Zhang, X., Walling, D. E., Quine, T. A., and Wen, A. (1997) Use of reservoir deposits and -137 measurements to investigate the erosional response of a small drainage basin of the rolling Loess Plateau region of China. *Land Degradation and Development,* Vol. 8, 1–16.

Zhang, X. and Zhang, Y. (1995) Use of Caesium-137 to investigate sediment sources in the Hekouzhen-Longmen Basin of the Middle Yellow River, China. In I. Foster, A. Gurnell, and B. Webb, eds., *Sediment and Water Quality in River Catchments*. London, UK: John Wiley and Sons, 353–362.