A southeastern piedmont watershed sediment budget: Evidence for a multi-millennial agricultural legacy

C.R. Jackson, J.K. Martin, D.S. Leigh, and L.T. West

ABSTRACT: A sediment budget was developed for a representative rural southeastern Piedmont watershed to estimate the relative importance of various sediment sources, particularly the contribution of agricultural sediments introduced to stream systems during the cotton-farming era (approximately 1820 to 1930 A.D.). The Murder Creek basin containing Monticello, Georgia was chosen because: 1) forestry and agriculture were and continue to be dominant land uses; 2) a U.S. Geological Survey (USGS) gage provided flow and suspended sediment records; and 3) the creek discharges into the Lake Sinclair reservoir (constructed 1949 to 1953), which could be used as a bedload sediment trap. Sediment rating curves, reservoir sediment deposition, and the Water Erosion Prediction Project (WEPP) and Universal Soil Loss Equation (USLE) erosion models were used to estimate suspended sediment export, bedload export, unpaved road erosion, and other surface erosion, respectively. Depths of historical agricultural sediment deposits were measured in stream cutbanks and floodplain auger holes. Historical row-crop agriculture led to floodplain deposition of a nearly-uniform 1.6 m (5.3 ft) of sediment, equivalent to 12.2 cm (0.40 ft) of topsoil over the watershed. The mass of cotton-farming sediments in valley storage was extremely large compared to current sediment export rates. At present sediment export rates, it would take six to ten millennia to remove all of the cotton-farming sediment in storage. This study suggests that the unstable streambanks, mobile sandy streambeds, and turbid conditions characteristic of modern Piedmont streams are largely a legacy of poor farming practices in the late 1800s and early 1900s. Estimated sediment exports exceed estimates of current inputs, and floodplain accretion rates and streambank conditions suggest streams have been in a state of net sediment export over the last 50 years.

Keywords: Erosion, fluvial geomorphology, sedimentation, sediment budgets, water quality

Sediment is the single most important water quality problem and the largest contributor by volume of non-point source pollution in the United States (Neary et al., 1988). In Georgia, especially the Piedmont Province, there is a past and present problem with sediment from non-point sources entering the state's waterways. In the southeastern Piedmont, sediment is a problem even in rural basins where little or no development is occurring. In 2002, over 140 rural Georgia stream and river segments either partially supported or did not support their designated uses due to impaired biotic conditions assumed to result from excessive sediment loads (GEPD, 2002). This situation raises questions about the sources of sediment problems and the relative magnitudes of different sources.

Sediment issues in the southeastern Piedmont are complicated by large volumes of sediment known to have been introduced to streams during the 1800's and early 1900's by poor row crop farming practices (Trimble, 1974; Richter and Markewitz, 2001). Today's forested hillslopes feature many inactive gullies formed during the row-crop agriculture era. However, most previous estimates of cotton-era erosion have been based on indirect estimation techniques, not on direct measurements of sediment budget components. Therefore, understanding sediment problems in this region, and placing current sediment inputs in the proper perspective, requires quantifying the role of historical agricultural sediments in current sediment dynamics.

Prior to European settlement, it is presumed that Piedmont streams ran clear under non-storm conditions, as described by several early explorers. Most of the study area was in hardwood and mixed forests until European settlers arrived. William Bartram, in his book, *Travels*, noted in 1775 that the Chattahoochee River "is about three or four hundred yards wide, carries fifteen or twenty feet of water and flows down with an active current; the water is clear, cool and salubrious" (Harper, 1998). Bartram also described the soils of the Georgia Piedmont as "a deep, rich, dark mould, on a deep stratum of reddish brown tenacious clay,…" (Harper, 1998).

The history of agricultural practices in this area of the Piedmont is well documented (Trimble, 1974: Richter and Markewitz, 2001). In the region of the Murder Creek watershed, cotton farming became widespread around 1820 (Gray, 1933) and ended abruptly around 1930. Analyzing farming practices of the 1800s, patterns of slave ownership, and cotton production, Trimble (1974) estimated that ten to thirty centimeters of native topsoil were lost during the late 1800s and early 1900s due to poor agricultural practices. Current soil surveys by the Natural Resources Conservation Service (NRCS) show that many of the Piedmont soils are highly eroded and have little or no topsoil. Poor farming practices during the cotton-farming era caused deep and large-scale erosion including gullies. It was reported that as much as 75 percent of Putnam County (which comprises a portion of the study basin) was cleared for agricultural practices (Marean, 1901). The early settlers reportedly would lay their crop rows up and down the slopes of the hills to obtain better drainage (Marean, 1901). Many of the gullies in this area formed along these drainage rows, and at the time of the first soil survey reports, many had developed into ravines. The following excerpt, from a January 31, 1933 speech by Hugh Hammond Bennett,

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chief of the Soil Conservation Service, describes the landscape of the Georgia and South Carolina Piedmont during a soil survey conducted in the year 1911:

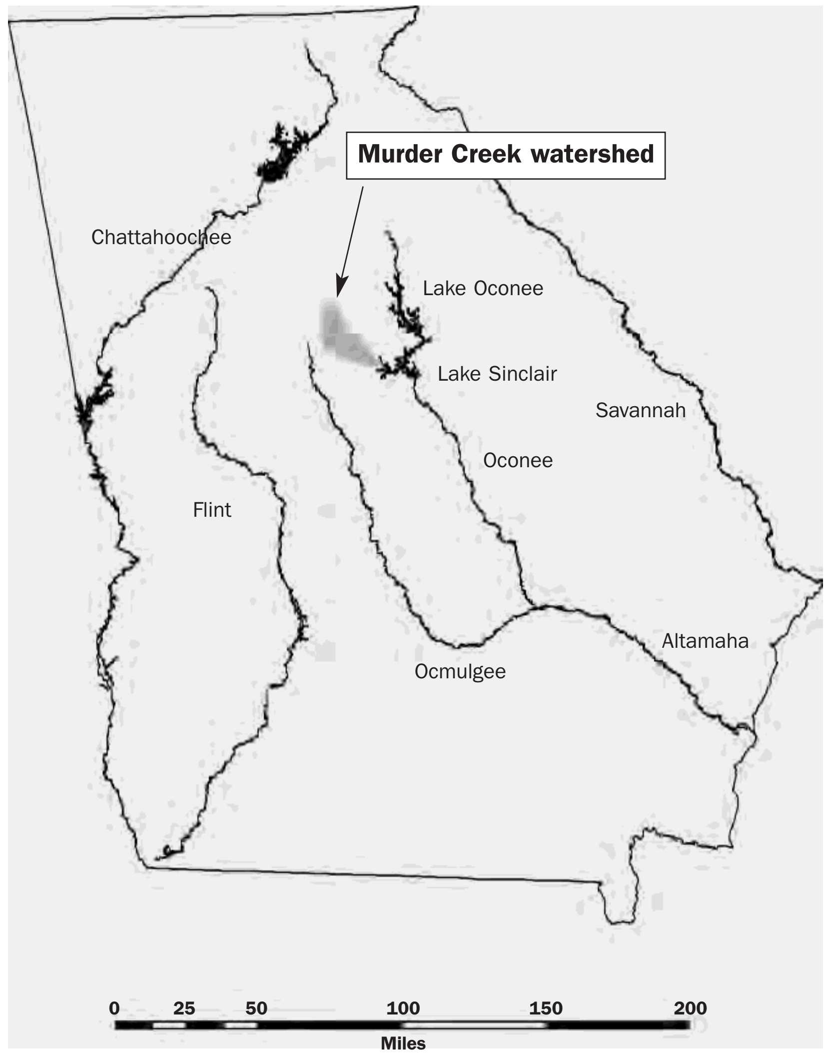
> "…46 thousand acres of stream-bottom, once the most productive soil of the entire state, were classed as Meadow, or land covered with sand and mud washed out of the cultivated hills, and thus made subject to increased overflows due to the choking of channel ways with the debris of erosion… I found on this second trip that the gullies had not stopped with their chiseling away of the fine agricultural lands. They had grown longer, deeper, and wider; they had branched out, forming new canyons. A roadway which I had traveled previously had been moved; it must be moved again. But it can be moved but once more, since yawning ravines are approaching from the opposite direction."

Once a gully was created by poor management practices and extended into the saprolite, large amounts of material moved from the hillslopes and into the stream valley. Glenn (1911) reported many of these gullies were forming in the Piedmont region, and that erosional processes downcutting through the soil mantle were largely left unchecked. The cotton-farming era ended abruptly in 1930 due to the Depression, falling cotton prices, boll-weevils, and depleted soils. Since 1930, much of the rural southeastern Piedmont reverted to or was planted to forest.

One way to evaluate relative contributions of various land use activities to total sediment load is to calculate a basin-wide sediment budget for a representative basin. A sediment budget attempts to quantify sediment inputs, internal storage volumes, and sediment export from the stream system. In rural basins in the Georgia Piedmont, typical sediment sources include silvicultural activities, row-crop agriculture, livestock operations, unpaved county roads, and eroding roadside ditches. One of the benefits of a sediment budget is that a relative ranking of sediment inputs by activity can help prioritize water quality improvements through the total maximum daily load (TMDL) process of regulation. A sediment budget in this setting also puts the influence of past row crop agriculture on stream systems into geomorphological perspective.

Figure 1

Location map of Murder Creek watershed relative to major rivers within the State of Georgia.



The Murder Creek basin, located in the lower Georgia Piedmont between the towns of Eatonton and Monticello and draining portions of Newton and Jasper as well as slivers of Putnam and Morgan Counties (Figure 1), was selected as the study watershed for a variety of reasons. Murder Creek is a sixth-order stream draining approximately 53,884 ha (209 mi^2) where it enters Lake Sinclair and 49,032 ha (190 mi^2) at the USGS gage (N 33°15.136' W83°28.884') about 5.5 km (3.4 mi) upstream of the basin outlet. Land use in the basin is characteristic of the rural Piedmont (Table 1). Dominant land uses are forestry and cattle farming, and there is some row-crop agriculture and rural residential land use. The basin includes a small town, Monticello, but no active urbanization. The basin drains into Lake Sinclair, which was constructed in 1949 to 1953, and sediment deposition in Lake Sinclair can be used to calculate a long-term average bedload estimate. Murder Creek has a USGS gage whose continuous flow record begins in 1977 and which provides sporadic measurements of turbidity (in NTU) and total suspended solids concentrations. Additionally, floodplains could be accessed on public lands and lands owned by cooperators (U.S. Forest Service, Weyerhaeuser, and PlumCreek).

Quantification of the sediment budget was achieved through the following sub-objectives:

1. Use geographic information systems (GIS) to characterize roads, agriculture, silvicultural activities, and other land use characteristics in the basin.
2. Estimate the volume and mass of agricultural sediments in valley storage by

Table 1. Land use within Murder Creek Basin as classified by Martin (2001) (see methods) and the University of Georgia geographic information systems (GIS) Center, and as selected for post- processing Universal Soil Loss Equation (USLE) results. Total watershed area draining to Lake Sinclair was 53,884 ha (209 mi²).

	Percent of watershed		
Land use	Martin classification	Univ. Georgia GIS Center classification (%)	USLE post-processing adjusted classification (%)
Forest *(Total)*	*83.07*	*74.7*	*82.4*
Mixed mature forest	46.10	33.0	45.7
Planted pine	20.55	31.8	20.4
Mixed regrowth	10.12	2.1	10.0
Clearcut	6.30	7.8	6.2
Pasture	7.72	13.0	13.0
Agriculture (row crops)	6.93	2.3	2.3
Wetlands	1.37	2.6	1.37
Open Water	0.63	nc	0.63
Urban	0.27	nc	0.27
Other (roads, urban, water)	nc*	7.3	—

* **nc: not classified.**

measuring depths to the pre-agricultural floodplain and multiplying by the NRCS active floodplain soils map area.

3. Estimate recent floodplain sediment accrual rates using the dendrogeomorphic techniques pioneered by Sigafoos (1964).
4. Estimate reservoir accumulation and deposition over the last 50 years and use these data to estimate annual bedload export from the watershed.
5. Estimate average annual suspended sediment export past the USGS gage using sediment rating curves developed from USGS suspended sediment data and additional data collected during this project.
6. Estimate sediment production from unpaved county, state and federal roads using the WEPP Road model.
7. Estimate sediment production from current land use activities using the USLE.

Trimble (1975) calculated that, within the Savannah River watershed, only four percent of the soil eroded from the Piedmont uplands since the 1700's had been carried past Augusta, Georgia. Much of the eroded sediment was believed to remain in valley storage and in transport in Georgia's Piedmont streams. Using the Murder Creek watershed, this study measured and quantified the agricultural sediment still in storage and also estimated bedload and suspended load export under modern conditions (the previous 47 years for bedload export and 26 years for suspend load export). The resulting sediment budget quantified the degree to which row-crop farming of the cotton-era has altered the long-term morphology of Piedmont rivers and should aid in the development of watershed management strategies.

Reservoir surveys have been found to be a valuable tool in volumetric analysis of sediment exported from a watershed (Schick and Lekach, 1993). For example, Beach (1992) used reservoir sedimentation to calculate an average soil loss rate for two watersheds. Similarly, in an arid watershed in Israel, reservoir surveys were used to improve suspended and bedload sediment export from a previous sediment budget created on the same watershed (Schick and Lekach, 1993). Dendy and Bolton (1976) used reservoir sedimentation surveys to evaluate the effect of drainage area and mean annual runoff on sediment yield. They found that as basin size increased sediment yield decreased. This indicated that less sediment was being transported out of the basin and more sediment was going into storage as basin area increased.

To predict erosion rates across a landscape, researchers often use the USLE (Wischmeier and Smith, 1978) because it is an easily applied predictive model and has been validated to accurately predict soil landscape erosion (Reid and Dunne, 1996). The USLE has been used to estimate erosion in numerous sediment budget studies (Beach, 1992; Trimble, 1983; Phillips, 1991; Faye et al., 1980). For example, Beach (1992) showed that reservoir sedimentation data and predicted total erosion by the USLE showed strong convergence in two different watersheds. The similarity between these numbers encouraged use of the USLE in estimating erosion rates from the Murder Creek basin.

Rural areas of the Georgia Piedmont feature many unpaved county roads where sediment contributions have not been adequately evaluated. Most relevant research has focused on sediment effects of logging roads. It has long been recognized that forest roads are a major contributor of sediment to water systems (Reid and Dunne, 1984; Swift, 1988; Ketcheson and Megahan, 1996; Megahan and Kidd, 1972). Logging roads are usually the source of much of the sediment that is produced during silvicultural activities (Hewlett and Doss, 1984; Swift, 1984). However, the sediment production from forest road activities usually decreases, or may even cease, when logging roads or skid trails are properly retired (Patric, 1976). In contrast, unpaved county roads are constantly maintained in order to keep roads accessible to vehicles. The practice of grading and maintaining roads leads to the displacement of large amounts of soil from the surface of the road and into the roadside ditch in a loose unconsolidated form. Clearly unpaved roads must be accounted for in a sediment budget as a source of sediment production within a watershed. The WEPP Road model (Elliot et al., 1999; Tysdal et al., 1999; Elliot, 1994) was developed specifically for this purpose and was used in this study to estimate sediment production from unpaved roads.

Methods and Materials

Following the general guidance and methodologies outlined by Reid and Dunne (1996), this project created a watershed-scale sediment budget quantifying valley storage of post-1820 sediment deposits, bedload sediment export, suspended sediment export, and current sediment contributions, specifically delivered sheet and unpaved road erosion estimated by USLE and WEPP Road, respectively. Valley storage of cotton-era sediments was estimated through identification of the contact between cotton-era sediment deposits and the prehistoric floodplain present before the onset of row-crop agriculture, and then estimating the volume of sediment deposits overlying the prehistoric floodplain. Bedload sediment export was estimated by calculating sediment accumulation in the Murder Creek arm of the Lake Sinclair reservoir. Export of total suspended solids was estimated from Murder Creek USGS gage station data by creating sediment rating curves and applying the fitted relationships to the entire 26+ year flow record (1977 to

2003). Current sediment contributions for all land uses within the Murder Creek watershed were estimated using the USLE and GIS. Additionally, sediment contributions from unpaved roads were estimated using the WEPP Road model developed by the U.S. Forest Service.

Depths from the floodplain surface to the pre-historic floodplain (the floodplain surface which existed before the onset of European agriculture, approximately 1820 A.D.) were measured using auger sampling at 20 locations throughout the watershed (Figure 2). Depths to the pre-historic floodplain were identified by locating the stratigraphic boundary between the pre-historic floodplain surface and the lower boundary of the historical floodplain sediments. The boundary is identified by a stratigraphic layer of sands (sands, loamy sands) with high mica content over a boundary of usually reduced soils with higher clay and low mica contents. Whenever possible, exposed streambanks at the location of the auger measurement were used to verify the measured depth to the pre-historic floodplain. NRCS county soil survey maps, digitized into GIS format, allowed for determination of the areal extent of floodplain soils, defined as Entisols and Inceptisols (Figure 2).

The measured depths of historical sediment deposits were compared against elevation, slope, Strahler stream order, and drainage area to determine if these variables were correlated to deposition depth (Figures 3a-d). Linear regression analysis was conducted to determine if any of these variables affected the depth to the pre-historic floodplain. Because no significant relationships were found (Figures 3a-d), the average depth to the pre-historic floodplain was multiplied by the total area of Entisols and Enceptisols to calculate the total volume of historical agricultural sediments in valley storage.

Dendrogeomorphic techniques (Sigafoos, 1964) were planned to estimate and quantify whether Murder Creek floodplain surfaces were aggrading, degrading, or not measurably changing in elevation. Burial of root crowns indicated aggradation since the time of tree establishment, and sedimentation rates could be estimated by measuring the depth of root crown burial and dividing by the age of the tree (determined by coring). The occurrence of root crowns at the soil surface indicated static floodplain elevations, while exposure of root crowns indicated net floodplain scour. Upon initiating the dendrogeomorphic investigations, it became clear that buried root crowns were uncommon. Therefore, root crown conditions of mature trees were surveyed using zig-zag transects across the floodplain. The observer zig-zagged from the streambank or natural levee (if present) to the edge of the active floodplain and categorized root crown conditions as either buried, at surface, or exposed by erosion on all trees within 10 m (32 ft) of the transect and with diameter at breast height greater than 30 cm (12 in). Four separate floodplain transects were surveyed and root conditions were categorized on 521 trees.

Original topographic survey sheets of the

Figure 2

Map showing locations where depth to pre-historic floodplain was measured using augers and streambanks. Map also shows spatial extent of all Natural Resources Conservation Service (NRCS)-mapped floodplain Entisol and Inceptisol soil series in the Murder Creek watershed. Entisols and Enceptisols were lumped together in the analysis and are not differentiated on the map. Streams are not portrayed on this map, but the locations of larger streams can be inferred from the floodplain soils. Gaps in the floodplain soil series occur where there are open bodies of water.

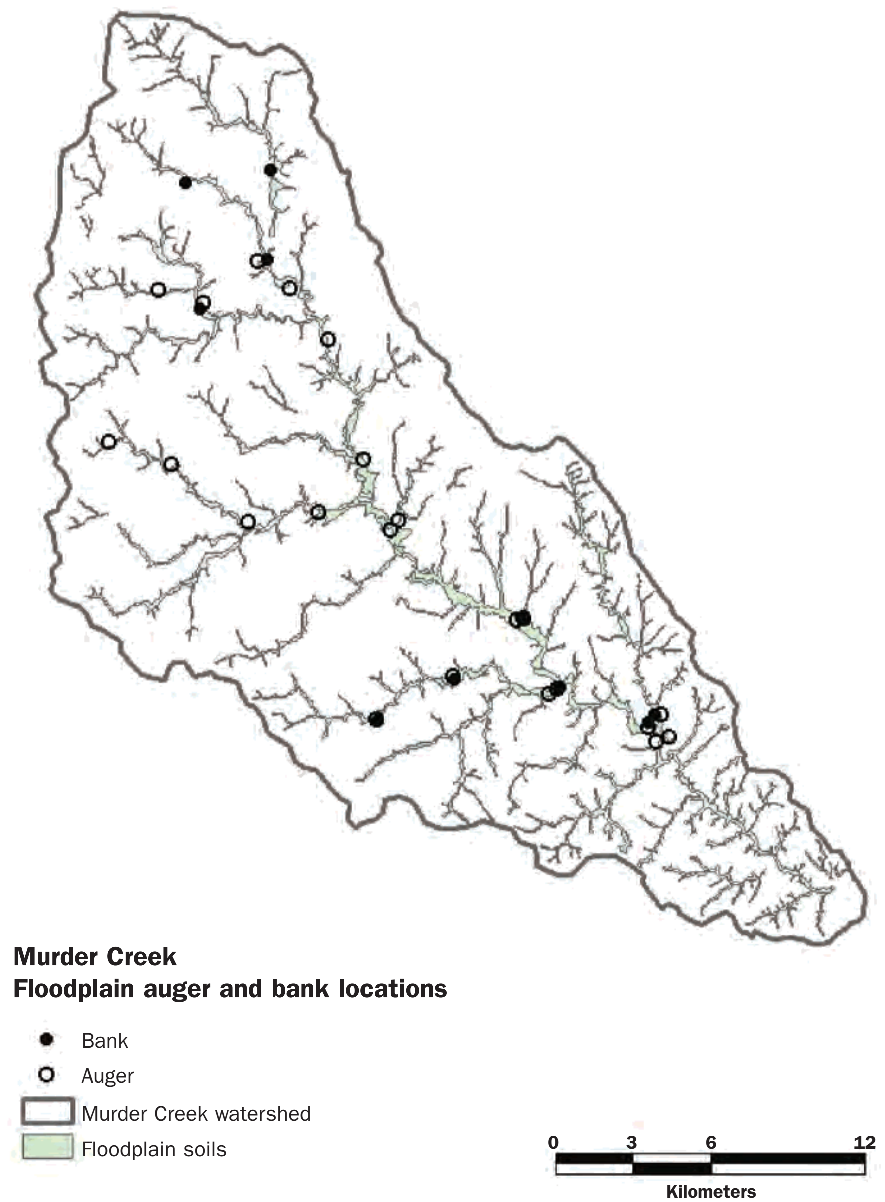
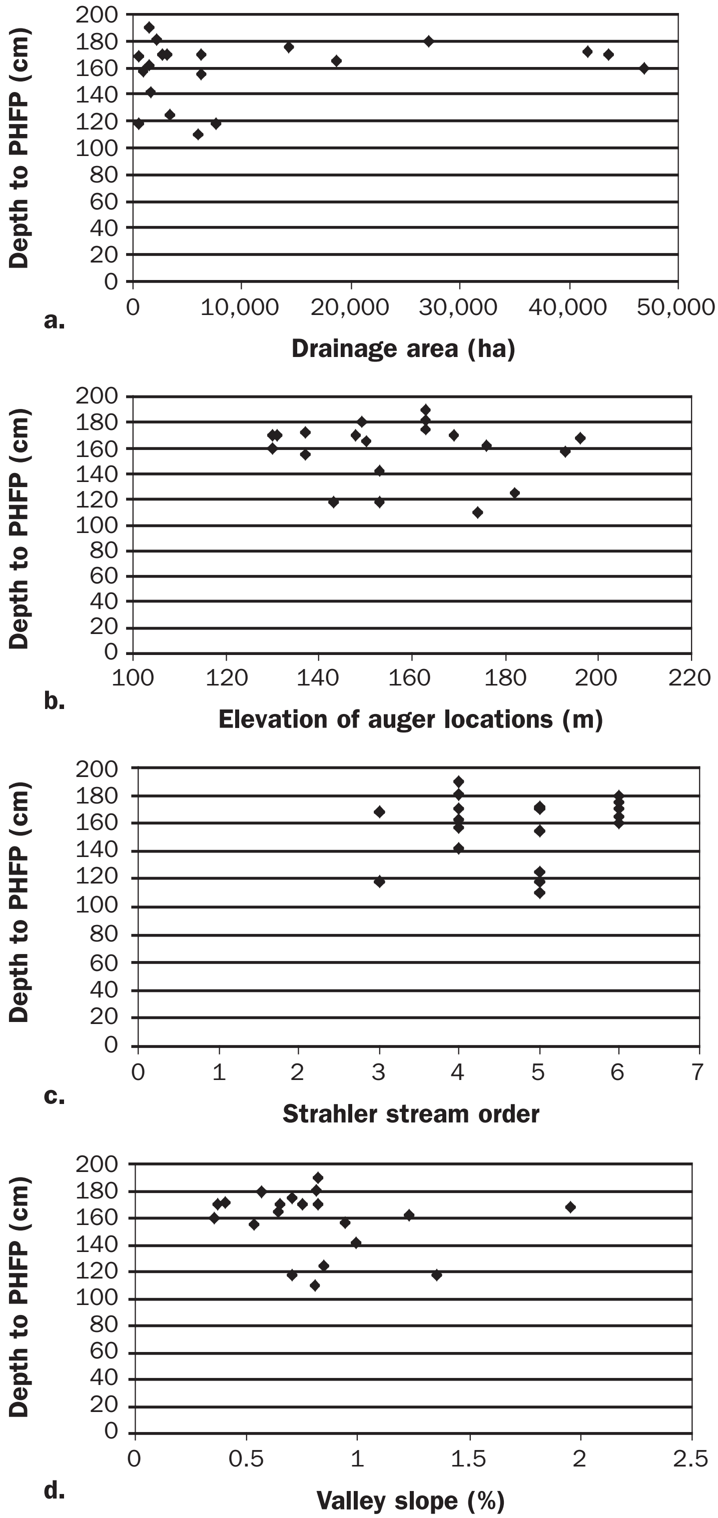


Figure 3a-d

Relationships between depth to the pre-historic floodplain (PHFP) and characteristics of each floodplain sample site: a) Drainage area of sample site, b) elevation of sample site, c) Strahler stream order at sample site, and d) valley slope at the sample site. Regression equations were not portrayed because there were no statistically significant relationships ($p>0.05$ in all four cases).



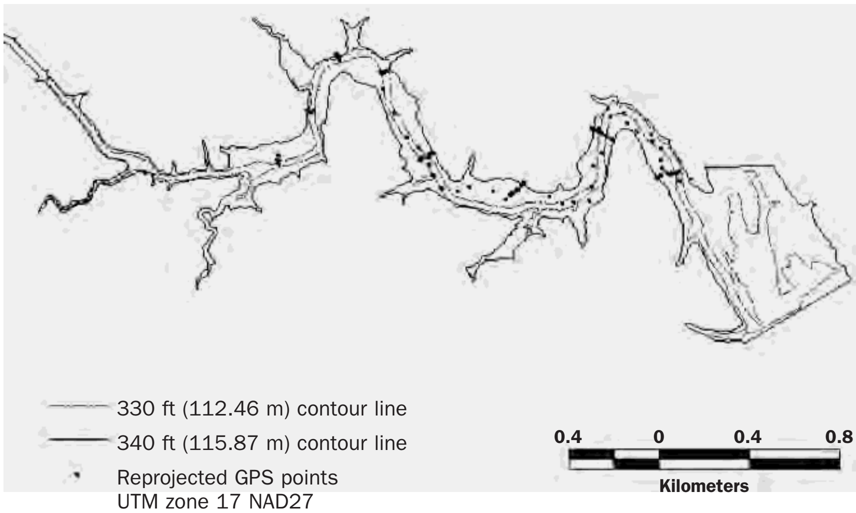
Murder Creek arm of Lake Sinclair surveyed before dam construction were obtained from Georgia Power. These survey sheets were digitally scanned and geo-referenced using USGS digital raster graphics maps. Using the geo-referenced original survey map, the contour lines were digitized in ESRI ArcView 3.2 (Environmental Systems Research Institute, Inc., 1999) into separate elevation themes. ESRI ArcView 3D Analyst (an extension to ArcView 3.2) was used to create a triangulated irregular network model from the digitized contour elevation values. The model was then converted from vector into raster data with elevation as the value for each cell.

A bathymetric survey was conducted on the Murder Creek arm of Lake Sinclair to quantify sediment deposition since dam closure in 1953 (Figure 4). Sediment elevations were obtained by lowering a weighted meter tape until the weight reached the top of the stored sediment in the Murder Creek arm of Lake Sinclair. Coordinates of the depth soundings were determined using a Trimble Geo-Explorer II GPS unit. Lake Sinclair pool elevations are recorded at the Georgia Power dam office on an hourly basis and were obtained to match the time of sediment elevation data collection. Sediment elevations were calculated by subtracting the depth to sediment from the pool elevation provided by Georgia Power.

Using inverse distance weighted interpolation, sediment elevation contours were created from GPS sediment attribute data. This process gave an areal extent of current sediment elevations across the Murder Creek arm of Lake Sinclair. From this theme, a triangulated irregular network model was created to represent current sediment elevations in the Murder Creek arm of Lake Sinclair. The sediment elevation triangulated irregular network model was then converted from vector into raster data with elevation as the value for each cell.

Using the constructed pre-dam closure and post-dam closure sediment grids, the ArcInfo CUTFILL command (ArcInfo 8.0, ESRI, 1999) was used to determine change in sediment elevations between the two time periods. CUTFILL calculates cut and fill volume between an "after" grid and a "before" grid for each contiguous cut or fill area (ESRI, 1999) yielding the volume of sediment in storage in the Murder Creek arm of Lake Sinclair. This volume was multiplied

Figure 4
Map showing where sediment elevations within Lake Sinclair were measured. Global positioning system points re-projected into the same coordinate system used in the pre-dam topographic map.



by the average bulk density of the deposited sediments to determine mass, and the resulting mass was divided by 47 years (elapsed time since dam closure in 1953) to estimate average annual bedload export.

During our surveys of Murder Creek's sediment delta with Lake Sinclair, we observed that some lakeside landowners had contracted for dredging sufficient to allow boat access to the main body of the lake. It was not possible to quantify how much dredging has occurred, so the bedload deposition estimate was low-biased.

Historical floodplain sediments in storage and bedload sediments deposited in Lake Sinclair were measured in terms of volume. It was necessary to convert these volumes to mass for comparison with other aspects of the sediment budget. Alluvial soils in the basin are dominated by the Chewacla, Congaree, and Toccoa soil series. Bulk densities for horizons in the upper 1.5 m (4.9 ft) of these soils range from 1.36 to 1.81 g/cm^3 (Perkins, 1987). The horizon depth weighted average of the bulk densities was 1.63 g/cm^3, and this value was used for the volume to mass conversions for the exposed floodplain soils. Ten ring cores (diameter = 8.5 cm, height = 6 cm) of sediment deposited in Lake Sinclair were sampled and oven-dried to estimate average bulk density of the bedload sediments in Lake Sinclair. Textures of the submerged bedload sediments ranged from sandy loams to silt loams, and the bulk densities ranged from 0.72 g/cm^3 to 1.39 g/cm^3 with an average bulk density of 1.13 g/cm^3. Shen and Julien's (1993) equation for estimating the specific weight of sediment deposits predicted 1.28 g/cm^3, which would increase the estimated bedload transport rate by 13 percent.

Sporadic measurements of total suspended solids and/or turbidity (50 samples taken by USGS and the authors between 1990 to 2005) were used to characterize the relationship between suspended sediment concentrations and discharge in Murder Creek (Figure 5). Some of the USGS samples included both total suspended solids and turbidity measurements in nepholometric turbidity units, while others measured only turbidity. It was necessary to develop a relationship between total suspended solids and turbidity to convert turbidity to total suspended solids when total suspended solids was not measured. However, concurrent measurements of total suspended solids and turbidity were too few (N = 15) to develop such a relationship. Therefore, concurrent total suspended solids and turbidity measurements from USGS gages on seven similar streams (all within 30 mi [48 km] of Murder Creek and all draining predominantly forested basins) were compiled and used to relate total suspended solids to turbidity (Table 2, Figure 6).

Fitted relationships between total suspended solids and discharge were then applied to the continuous flow record (1977 to 2003) to estimate suspended sediment loads. Sediment rating curve techniques have long been used to estimate suspended sediment loads from continuous flow records and sporadic sediment concentration measurements when suspended sediment concentrations are correlated with discharge (Miller, 1951; Walling, 1977; Preston et al., 1989). However, infrequent sampling of skewed distributions can lead to bias, and multiple investigators have addressed the tendency for conventional rating curve methods to underestimate true loads (Ferguson, 1986; Thomas, 1988; Cohn et al., 1989; Preston et al., 1989). The minimum variance unbiased estimator (Cohn et al., 1989; Cohn et al., 1992) corrects the standard rating curve approach (the typical form of which relates the log of concentration to the log of discharge) to provide the least biased load estimates. To account for variations in rating curve predictions, Cohn's minimum variance unbiased estimator correction was used to fit the following three models (Figure 5a):

Model 1

$$\mathrm{Ln}\,[L] = 8.3248 + 1.4199\,\mathrm{Ln}[Q] + 0.0761\,\mathrm{Ln}[Q]^2 \text{ and}$$

$$\mathrm{Ln}\,[C] = 2.9400 + 0.4199\,\mathrm{Ln}[Q/4.49] + 0.0761\,\mathrm{Ln}[Q/4.49]^2$$

Model 2

$$\mathrm{Ln}\,[L] = 7.722 + 1.0759\,\mathrm{Ln}[Q] + 0.0633\,[Q]^{0.5} \text{ and}$$

$$\mathrm{Ln}\,[C] = 2.3371 + 0.07559\,\mathrm{Ln}[Q/4.49] + 0.0633\,[Q]^{0.5}$$

Model 3

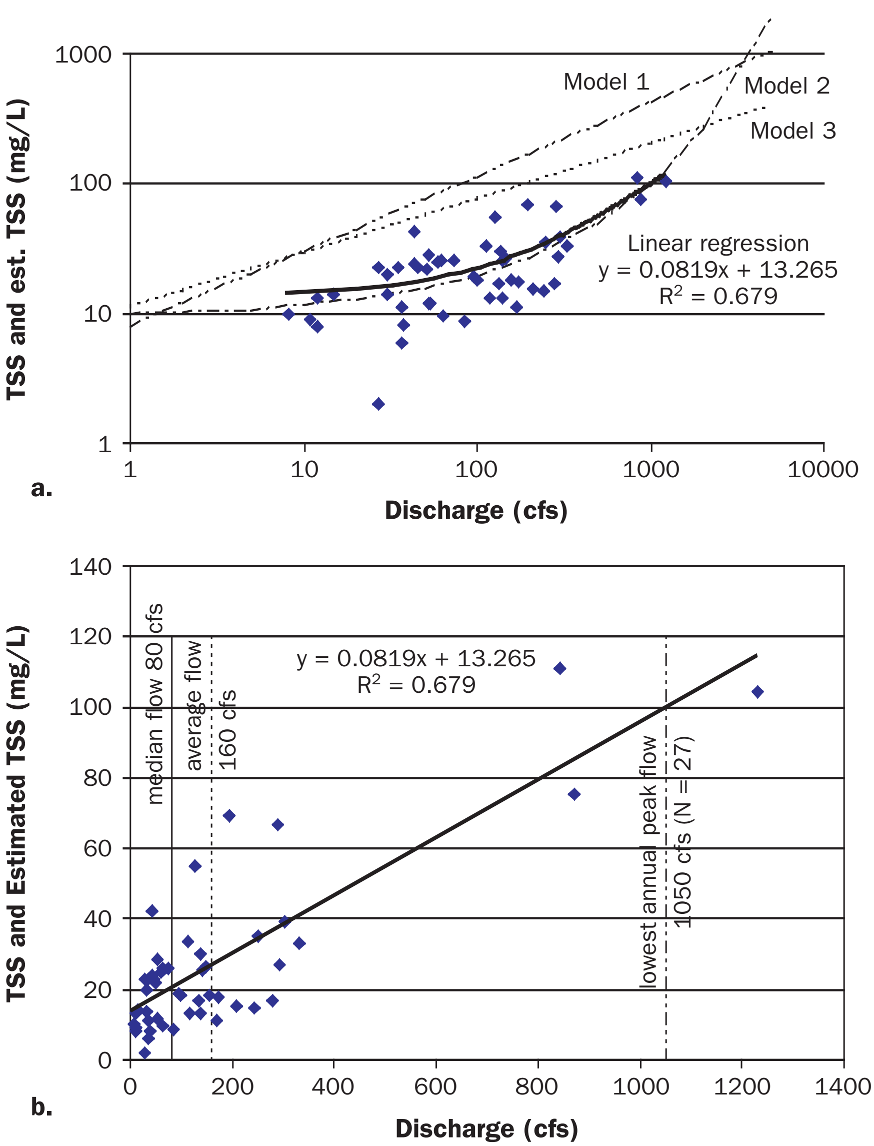
$$\mathrm{Ln}\,[L] = 8.4190 + 1.4199\,\mathrm{Ln}[Q] \text{ and}$$

$$\mathrm{Ln}\,[C] = 3.0341 + 0.4199\,\mathrm{Ln}[Q/4.49]$$

where,
L = Load, Kg dy^{-1},
C = Concentration, mg L^{-1}, and
Q = Average daily discharge, ft^3 s^{-1}

Each of these models was evaluated with respect to the r^2 for predicting concentration, the r^2 for predicting load, the p value for each variable, and the serial correlation of residuals (Table 3). With one exception, all three models were acceptable with respect to these metrics, and each model exhibited a statistical advantage over the other. In Model 2, the Ln [Q] variable was not statistically significant for predicting concentration ($p = 0.69$), but this variable was significant for predicting load ($p = 0.000001$). In addition to these minimum variance unbiased estimator models, the following linear regression was

Figure 5a-b
Sediment rating curves for Murder Creek developed from USGS gage data and additional data collected by authors: a) all four rating curve models and the total suspended solids (TSS) versus discharge data shown in log-log space; and b) linear regression model and TSS versus discharge data shown in arithmetic space along with Murder Creek median flow, average flow, and annual peak discharge.



used to estimate total suspended solids from discharge (Figure 5b) and to calculate loads for each day in the discharge record:

C = 13.265 + 0.0819 Q
L = k C Q Linear regression model

where,
k = unit conversion factor

The accuracy of these rating curve estimates of suspended load transport were limited by the small number of sediment samples taken during high flows and by the seasonal differences in the sediment/flow relationships. The three data points with the highest flows corresponded approximately to the annual flood (1.01 year flood) for Murder Creek, approximately 1,050 cfs or 29,715 L/s. For comparison, the 2-year flow for Murder Creek was 3,830 cfs or 108,000 L/s. However, suspended sediment rating curves developed for six other similar Georgia streams and rivers suggest that these extrapolations safely estimate sediment/flow relationships at higher flows (Faye et al., 1980; Holmbeck-Pelham and Rasmussen, 1997). By fitting several rating curve models to the data we estimated a range of suspended sediment loads. Additionally, the sediment budget results demonstrated that the uncertainty in the suspended sediment load estimation had no bearing on the interpretation of the sediment budget components.

The Universal Soil Loss Equation (USLE, shown in equation 1), developed by Wischmeier and Smith (1978), was chosen to estimate sheet erosion across the watershed, and sediment delivery ratios were used to estimate current contributions of sheet erosion to the stream system.

A = R K LS C P (1)

where,
A = Annual soil loss (t ac^{-1} yr^{-1})
R = Rainfall erosivity index (275 for Murder Creek basin)
K = Soil erodibility factor
LS = Slope length and steepness factor
C = Cover management factor
P = Conservation practice factor

A GIS model was created to run USLE over the entire watershed on a 30 m digital elevation model grid as described below, and some post processing was conducted to correct errors in land cover classifications.

A digital soil database was not available, except for a small portion in the northern part of the watershed contained in Morgan County, so a new soil database was created to provide spatially distributed soil descriptions. Soil erosivity (K) factors associated with the soils in the Murder Creek watershed were obtained from the Jasper, Newton, and Putnam Counties Soil Surveys (Lathem, 2004; Lathem, 2000; Payne 1976). Large scale (1:20,000) soil survey sheets from the local NRCS office were digitized to create the database.

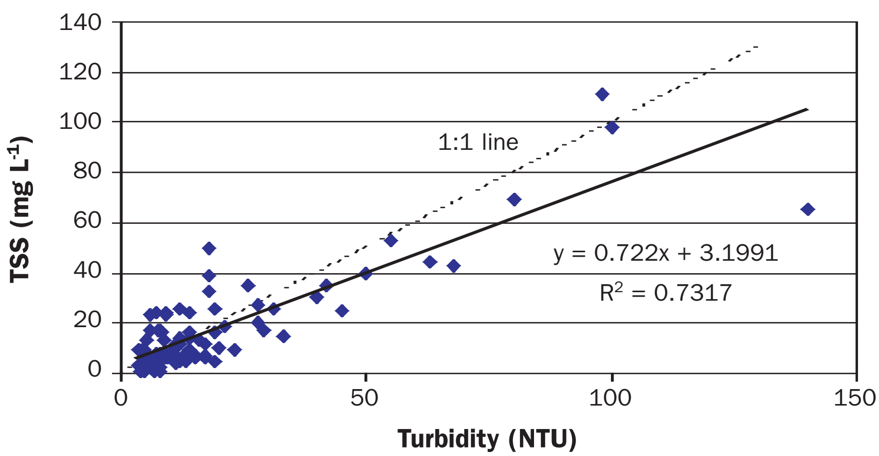
Slope length and slope steepness factors (LS) were created using digital elevation models. Digital elevation model data were obtained from the Georgia Spatial Data Clearinghouse (Georgia GIS Data Clearinghouse, 2000). Flow directions and accumulations were calculated using ArcInfo FLOW DIRECTION and FLOW ACCUMULATION commands, and slopes were calculated using ArcInfo Slope command (ArcInfo 8.0, ESRI, 1999). Slope length and slope steepness factors were then assigned to

Table 2. Description of nearby U.S. Geological Survey (USGS) gages from which data was compiled to create regressions to predict total suspended solids (TSS) concentrations (mg/L) from turbidity data in nephelometric turbidity units (Figure 6).

Stream	USGS gage number	Drainage area (mi^2)	Number of concurrent TSS and turbidity samples
Town Creek - Greensboro	02220368	7.3	16
Richland Creek - Greensboro	02220370	30.6	1
Rooty Creek - Eatonton	02220740	19.3	14
Little River - Godfrey	02220800	77.1	15
Big Indian Creek - Madison	02220850	29.5	14
Little River - Eatonton	02220900	262	8
Big Cedar Creek - Eatonton	02221900	133	14
Murder Creek	02221525	208	15
		Total	**97**

Figure 6

Relationship between total suspended solids (TSS) (mg/L) and turbidity (nepholometric turbidity units) in Murder Creek and seven nearby similar streams (see also Table 2).



grid cells using a conditional statement and the lookup table in Agricultural Handbook No. 537 (Wischmeier and Smith, 1978). Once the necessary data had been created, the data was converted into a 30 m (X ft) grid with the associated slope length and steepness factors.

Cover management factors were taken with USDA-NRCS guidance (USDA, 2000). A cover management factor for clear cut areas was taken from an unpublished Ph.D. dissertation which developed cover management factors for clear cut sites in the Georgia Piedmont (Burns, 1978). The modeled cover management factors were compared to values used in TMDL assessments by the Georgia Environmental Protection Division to maintain consistency with erosion estimation used in the TMDL process (Table 4).

Table 3. Statistical performance of the minimum variance unbiased estimator rating curve models for estimating total suspended solids concentrations and loads as a function of discharge.

Model	R^2 for concentration predictions	p-values for regression coefficients for each concentration model variable. (variable: p-value)	R^2 for load predictions	p-values for regression coefficients for each load model variable. (variable: p-value)	Serial correlation of residuals
Model 1	.448	Ln[Q]: <0.001 Ln $[Q]^2$: 0.111	.897	Ln[Q]: <0.001 Ln $[Q]^2$: 0.111	.257
Model 2	.458	Ln[Q]: 0.695 $[Q]^{0.5}$: 0.062	.899	Ln[Q]: <0.001 $[Q]^{0.5}$: <0.001	.280
Model 3	.418	Ln[Q]: <0.001	.892	Ln[Q]: <0.001	.166

Murder Creek land cover was determined from 1998 LANDSAT imagery including both summer (leaf on) and winter (leaf off) images. Using ERDAS Imagine 8.4 Interpretation Software (Leica Geosystems, 2001), land use was classified and separated into nine different categories (Table 1). Agricultural land from 1988 multi-resolutional land characteristics data obtained from Georgia Department of Natural Resources was used to subset the 1998 LANDSAT Image. The image was reclassified to further refine the agricultural land use. This was done because some of the agricultural land from the 1988 data had since been converted into pine plantation. An unsupervised classification procedure was used to determine the remaining land use category clusters that were not separated from the 1988 multi-resolutional land characteristics data. During field sampling the land use of much of the Murder Creek watershed was observed and located. It appeared that the cover classification overestimated row crop agriculture in the watershed. As the project progressed, the Georgia GIS clearinghouse released a classification of the Murder Creek watershed also based on 1998 LANDSAT imagery (Georgia GIS Data Clearinghouse, 2000). These classifications were compared and a composite classification (discussed later) was used to post-process the USLE modeling (Table 1).

Each cell that had been classified as row crop from the image classification was assigned a P factor. P factors ranged from 0.8 to 1.0 and were dependent upon slope and row grade percentage as defined by a lookup table in the Georgia USLE Resource Area Handbook (USDA-NRCS, 2000). The P values were based upon an assumption of a row grade of two percent and slope determined from the digital elevation model.

All factors were input into GIS raster format to calculate gross watershed erosion based upon land use. Each variable was created as a unique layer and assigned the appropriate variable. Once completed and the model was run, each cell in the watershed had a unique value that represented annual soil erosion. These values were averaged

Table 4. Land cover classification (C) factors used in the Universal Soil Loss Equation in calculating gross watershed erosion. C factor values that Georgia Environmental Protection Department (EPD) has used for other regions in the state were taken into consideration for consistency in erosion estimates.

Georgia EPD land cover classifications	Georgia EPD C factor	Modeled C factor	Notes
Open water	0.00	0.00	No erosion from open water.
Urban		0.02	
Low intensity residential	0.02	—	Low intensity residential C factor was used because the watershed contains little active urbanization. The largest municipality in the watershed is Monticello. Also, there is no classification of commercial/industrial in the watershed.
High intensity residential	0.005	—	
Commercial/industrial	0.003	—	
Clear cut	0.0018	0.013	C factor taken from values calculated on clear cuts in the Georgia Piedmont (Burns, 1978).
Mixed deciduous/evergreen	0.001	0.0001	C factor taken from the NRCS regional based values for Georgia (USDA, 2000).
Planted pine	0.001	0.001	C factor taken from the NRCS regional based values for Georgia (USDA, 2000).
Pasture	0.0033	0.003	C factor taken from the NRCS regional based values for Georgia (USDA, 2000).
Row crop agriculture	0.15824	0.16	C factor based on corn and small grain agriculture with 30 percent conservation tillage employed. Taken from the NRCS regional based values for Georgia (USDA, 2000).
Wetlands	—	0.007	C factor based on the average of the Georgia EPD wetland values.
Emergent herbaceous/wetlands	0.003	—	
Woody wetlands	0.011	—	
Mixed re-growth	—	0.003	Mixed re-growth was classified as land that was either abandoned fields/pasture or silvicultural sites greater than 3 years. Taken from the NRCS regional based values for Georgia (USDA, 2000).
Transitional	0.002	—	
Other grasses	0.003	—	

across land use types, and the resulting annual erosion rates were applied to the total area of each land use.

After running the USLE model as described above, additional information strongly suggested that the area of row crop agriculture had been overestimated. First, windshield surveys indicated that several locations classified as row crop were in fact hay fields. Second, the University of Georgia GIS center land cover classification was published (Table 1) and it estimated only 2.3 percent row crop agriculture and 13.0 percent pasture, as opposed to 6.93 percent and 7.72 percent estimated by Martin (2001). This distribution of farmland was more consistent with that observed in windshield surveys. Finally, the county profiles in the 2002 Census of Agriculture (USDA-NASS, 2004) corroborated the University of Georgia GIS center classification. Because of the high cover management factors associated with row crop lands, the total estimate of current sediment inputs was very sensitive to overestimation of row crop coverage. Therefore, a melded classification was developed that used Martin's classification categories but corrected the coverages based on the University of Georgia GIS center classification and the USDA-NASS data for farm land. The per area gross erosion estimates for each land use category calculated by the GIS system (Table 5) were then multiplied by the adjusted areas to calculate total gross erosion for each land use.

The USLE was designed to estimate sheet erosion on the land surface, not to estimate sediment delivery to streams. Much of the eroded soil is deposited lower on the landscape before reaching streams. Delivery ratios account for the deposition of eroded sediments on the hillslope, on floodplains, and within the stream channels. The probability of particle entrapment increases with the size of the drainage area (Dendy and Bolton, 1976; Shen and Julien, 1993), so the selection of an appropriate delivery ratio is a matter of scale. On forest clearcut operations in the Georgia Piedmont, Ward and Jackson (2004) found that only 25 percent of eroded soils predicted by USLE reached the base of the hillslope, and they found that over 70 percent of the remaining sediment being transported across the floodplain was deposited in the first 12 m (40 ft) of the floodplain. For the purpose of this sediment budget, the appropriate area to consider was the 190 mi^2 watershed draining to the USGS gage, as the current inputs were compared to exports at that point. Delivery ratios were calculated using the following equations from Shen and Julien (1993) and USDA Soil Conservation Service (1983):

$$SDR = 0.31\ A^{-0.3} \tag{2}$$

$$SDR = 0.417762\ A^{-0.134958} - 0.127097 \tag{3}$$

where,

SDR = Sediment delivery ratio (fraction of eroded sediment reaching measuring point in a stream or river)

A = Drainage area (mi^2)

For the 190 mi^2 Murder Creek watershed, these equations predict sediment ratios of 0.06 and 0.08, respectively. Additionally, Stewart et al. (1975) estimated a delivery ratio of 0.08 for 200 mi^2 agricultural watersheds. Therefore, delivery ratios of 0.06 and 0.08 were used to estimate current erosion contributions to the sediment budget. The sediment delivery ratios were applied outside of

Table 5. Summary of Universal Soil Loss Equation (USLE) and WEPP Road modeling results. Total erosion calculated for watershed area draining to U.S. Geological Survey gage (49,032 ha or 190 mi^2).

Land cover type	Percent of watershed	Area (ha)	Gross unit area erosion (Mg ha^{-1} yr^{-1}) - estimated by USLE or WEPP: Road GIS modeling	Total watershed erosion (Mg yr^{-1}) -estimated by USLE GIS modeling	Estimated sediment yield (Mg yr^{-1}) SDR = 0.06	Estimated sediment yield (Mg yr^{-1}) SDR = 0.08
Mixed mature forest	45.8	22349	0.02	447	27	36
Planted pine	20.4	9955	0.20	1991	119	159
Mixed regrowth	10	4880	0.24	1171	70	94
Clearcut	6.2	3025	2.64	7987	479	639
Forest *(total)*	*82.4*	*40210*		*11596*	*696*	*928*
Pasture	13	6344	0.41	2601	156	208
Agriculture (row crops)	2.3	1122	21.97	24658	1479	1973
Wetlands	1.4	683	4.60	3143	189	251
Open water	0.6	293	0.00	0	0	0
Urban	0.3	146	3.10	454	27	36
Other *(total)* [wetlands, open water, urban]				*3596*	*216*	*288*
Roads		234	59	13806	828	1104
Totals	**100**	**49,032**		**56,258**	**3,375**	**4,501**

the GIS system to the gross erosion estimates developed with USLE.

Sediment contributions from unpaved county roads (not including private roads) were estimated using the WEPP:Road model. WEPP Road is designed to predict runoff and sediment yield from roads and compacted soils (log landings, skid trails, vehicle tracks) and allows the user to define factors controlling road erosion including climate, road surface condition, topography, drain spacing, road design, and ditch condition (Elliot et al., 1999; Tysdal et al., 1999; Elliot, 1994). The road network for Murder Creek was obtained from the Georgia GIS Data Clearinghouse and overlaid on the stream hydrography layer with a 100 ft buffer on the streams to identify road and stream intersections and also locations where unpaved roads traveled near streams. Field reconnaissance was conducted to categorize all roads as paved or unpaved. A total of 341 km (212 mi) of unpaved public roads were identified in the watershed. The average width of unpaved roads was 6.87 m (22.3 ft), and the total area was 234 ha (581 ac). 86 unpaved road segments crossed or passed within 100 feet of a stream, and these were named contributing road segments. WEPP Road was applied only to these 86 road segments, which comprised 20 km (12.4 mi) of the unpaved road system, and each contributing road segment was visited to gather data for WEPP Road. WEPP Road includes sediment delivery estimation based on characteristics of the road and the road drainage system, but this sediment delivery ratio is inconsistent with the watershed-wide sediment delivery ratio applied to the USLE gross erosion estimates. Therefore, it was decided to apply the average gross erosion from the 86 surveyed segments to the entire unpaved road network and then use the same sediment delivery ratios applied to the USLE predictions. However, this was likely a biased sample because road segments approaching stream crossings were generally steeper than roads running on ridgetops or contours. This overestimation of sediment from unpaved county roads is balanced by the fact that this assessment did not include private unpaved roads such as logging roads, farm access roads, private roads, and driveways nor did it include ditches or cutslopes associated with paved roads.

Results and Discussion

Depth to the pre-historic floodplain showed no apparent or statistically significant relationships (all p values greater than 0.05) to basin area, elevation, stream order, or valley slope (Figures 3a-d). At the scale of this watershed, sediment from the cotton-farming era was evenly distributed over the entire stream network, inundating the floodplains to a relatively uniform average depth of 1.6 m (5.3 ft) determined from the auger measurements. Furthermore, 83 percent of the floodplain trees with diameter at breast height greater than 30 cm showed no evidence of aggradation or degradation, as the root crowns occurred at the ground surface, while only 9.6 percent of such trees showed evidence of aggradation and 7.2 percent indicated floodplain degradation. It was inferred that neither floodplain aggradation nor degradation had occurred over the last half-century.

The volume of sediment deposited in Lake Sinclair in the 47 years between dam closure and the bathymetric survey was 160,000 m^3. Applying the average measured bulk density of 1.13g/cm^3, this translated to 181,000 Mg (199,000 tons) or an annual bedload transport rate of 3850 Mg yr^{-1} (4240 t yr^{-1}) over the 47 years since dam closure. This is considered to be a low-biased estimate due to unaccounted dredging for recreational boat access.

Using the four different rating curve models, annual suspended sediment load was estimated as 10,063 Mg yr^{-1}, 13,485 Mg yr^{-1}, 7033 Mg yr^{-1}, and 11,392 Mg yr^{-1} (11,070, 14,830, 7740, and 12530 t yr^{-1}) for Models 1, 2, 3 and the Linear Regression model, respectively. The variation in these models was due to the need for rating curves to extrapolate beyond available data relating total suspended solids to discharge. In this case, the highest flows for which total suspended solids data were available corresponded to the annual flood while most sediment transport occurs during larger flows.

GIS-calculated USLE estimates of annual erosion rates for each individual land provided reasonable estimates for the Georgia Piedmont (Table 5), and current activities account for 19 to 41 percent of current sediment exports from the watershed (Table 6). Forest management activities were estimated to contribute 696 to 928 Mg yr^{-1} (765 to 1020 t yr^{-1}) to current sediment exports due to the processes of harvesting, site prepara-

Table 6. Murder Creek Basin sediment budget summary.

	Mg
Cotton-era agricultural sediment in storage:	107,000,000
Sediment exports at the USGS gage:	**Mg yr^{-1}**
Bedload	3,850
Suspended load (based on different rating curves)	
MVUE Model 1	10,060
MVUE Model 2	13,490
MVUE Model 3	7,030
Linear regression	11,390
Range of total exports	10,880 - 17,340
	Years
Ratio of stored agricultural sediment to exports	6170 to 9800
Contributions of current erosion to exports:	**Mg yr^{-1}**
Forests	696 - 928
Row crop agriculture	1479 - 1973
Pasture	156 - 208
Other land uses	216 - 288
Unpaved roads (range)	828 - 1104
Total contributions of current erosion to exports	3375 - 4501
Ratio of current contributions to total export	**0.19 - 0.41**

tion, and re-growth of forest land (Table 6). Row-crop agricultural activities were estimated to yield 1479 to 1973 Mg/yr (1627 to 2170 t yr^{-1}), and the estimates for pastures were 156 to 208 Mg yr^{-1} (172 to 229 t yr^{-1}). Other land uses were estimated to yield 216 to 288 Mg yr^{-1} (237 to 316 t yr^{-1}). Unpaved county roads were estimated to yield 828 to 1100 Mg yr^{-1} (911 to 1210 t yr^{-1}). If the undelivered portion of current erosion rates were all assumed to deposit on the floodplain in the 70 years since the end of the cotton era in 1930, this would account for at most three percent (or 5 cm) of the floodplain sedimentation since the beginning of the cotton era in 1820.

Table 6 summarizes the sediment budget for the Murder Creek watershed. The volume of cotton-farming era sediments in floodplain storage was calculated to be 66,000,000 m^3 (72,000,000 yd^3), and the mass was estimated as 107,000,000 metric tons (118,000,000 t). This translates to 12.2 cm (0.400 ft) of topsoil erosion over the whole watershed. Total erosion per unit area over the cotton-farming era necessary to produce this much sediment is 1986 Mg ha^{-1} (881 t ac^{-1}). Assuming a duration of 110 years from 1820 to 1930 (Gray, 1933), the average erosion rate during this era was 18.05 Mg ha^{-1} yr^{-1} (8.01 t ac^{-1} yr^{-1}). These estimates do not account for sediment transported out of the watershed during the cotton-farming era, and these estimates agree with Trimble's previous estimates of 11 to 31 cm (0.36 to 1.02 ft) of Georgia Piedmont erosion during this era (Trimble, 1974).

Total annual sediment export from the basin, calculated as the sum of bedload and suspended load transport, was estimated between 10,880 and 17,340 Mg yr^{-1} (11,970 to 19,070 t yr^{-1}), depending on the suspended sediment rating curve model. The bedload component of the total sediment load was 3850 Mg yr^{-1} (4200 t yr^{-1}), accounting for 22 percent to 35 percent of total sediment load. In a review of sediment budgets from around the world, Reid and Dunne (1996) found that bedload accounted for 20 to 75 percent of total load in sand-bedded streams. Relative bedload transport in Murder Creek is consistent with this range and also with data from the nearby Chattahoochee River system (Faye et al., 1980).

Ignoring current sediment inputs to the system, the mass of cotton era sediments in valley storage were 6170 to 9800 times greater than the total annual sediment load of the watershed under present conditions. In other words, it would take Murder Creek six to ten millennia to excavate and transport all of the sediment estimated to have deposited on the floodplains during the cotton-farming era, even if current sediment inputs were zero. Thus, the farming practices of the 1800's and early 1900's will leave an imprint on Piedmont valley morphology for a time period equivalent to the current duration of human civilization.

Based upon our estimates of inputs from various sources and exports via total suspended solids and bedload, sediment exports were greater than sediment inputs. This surplus was calculated between 6380 and 14000 Mg yr^{-1} (7020 and 15360 t yr^{-1}). It was assumed that the remainder of the sediment came from excavation and mobilization of stored valley sediments, principally through lateral migration of stream channels and bank erosion.

The results were substantiated by our observations of geomorphic conditions in the watershed. We observed that most of the streambanks in the system were steep and unstable. Low order streams were highly incised, as was also observed in nearby stream systems by Ruhlman and Nutter (1999). Larger order streams were not as consistently incised, but still possessed steep and eroding streambanks. Everywhere except in shoal areas, channel beds were composed of loose and highly mobile sands. Inset vegetated bars were forming in some streams. Floodplain surfaces showed no consistent signs of elevation change over the last 50 years. All of these stream conditions were consistent with a stream system that is eroding valley sediments after a period of high sediment input and valley aggradation.

Bank erosion rates necessary to produce the inferred contribution of remobilized valley sediments to the annual export from the watershed were quite small, in the range of 0.21 to 0.46 cm yr^{-1} (0.0069 to 0.015 ft yr^{-1}), given a total channel length of 595 km and an average bank height of 1.58 m. Reported bank erosion rates measured in other humid mid-latitude streams vary widely, from 0 to 1.0 m yr^{-1} (Knighton, 1998). Improving this sediment budget through the use of erosion pins or through repeated cross sections would require many sample points monitored over a long period of time.

Accuracy of each aspect of the sediment budget presented here was subject to error, but the main findings that: 1) the mass of cotton-farming sediment in valley storage was extremely large compared to current sediment export, and 2) current exports exceeded current sediment inputs were both robust in that improved accuracy in any or all of the components of the sediment budget would not change these findings. Probably the least well supported aspect of this study was the use of literature-based watershed scale sediment delivery ratios. While the values used in this study seem reasonable with respect to field observations at the site scale (Ward and Jackson, 2004), the authors were unaware of any watershed scale sediment delivery ratios calibrated for the southeastern Piedmont. Error in these delivery ratios easily could be as large as 50 percent. Road erosion estimations also featured weaknesses. Information and access was unavailable to estimate erosion from private unpaved roads, and estimation of ditch and cutslope erosion from the hundreds of kilometers of paved roads was beyond the scope of this project. Suspended sediment load estimation was also difficult due to the unavailability of total suspended solids measurements during large flood events. The highest estimate of suspended sediment load (minimum variance unbiased estimator Model 2) was 92 percent larger than the lowest estimate (minimum variance unbiased estimator Model 3).

Even with the relative scarcity of total suspended solids data at high flows, Murder Creek was nearly ideal for assessing the effects of cotton-era farming on Piedmont stream conditions due to the USGS gage data, the availability of pre-project and current topography of Lake Sinclair, and the accessibility of floodplains. Furthermore, the sediment budget uncertainties were almost inconsequential when considered against the magnitude of cotton farming era sediments deposited on the floodplains, and the current channel and floodplain geomorphology were only possible in a watershed where outputs exceed current inputs.

Summary and Conclusion

Valley deposits of agricultural sediment from the cotton farming era is equivalent to 12.2 cm (0.400 ft) of topsoil erosion over the whole watershed. This sediment budget provides direct corroborating evidence of Trimble's (1974) estimates of 11 to 31 cm of Piedmont erosion during the cotton farming era. It also corroborates Meade and Trimble's (1974) finding that suspended sediment concentrations in southeastern rivers dropped dramatically in the decades following 1930.

It is not necessary for Piedmont streams to excavate all of the cotton era sediments in order to reach new quasi-equilibrium states and recovery can be expected to occur much faster than six to ten millennia, but recovery will take a long time. This project did not conduct analyses appropriate for determining the time to recovery in rural Piedmont basins, but it is appears to be in the order of centuries. Basin-wide sediment transport and stream morphology modeling techniques appropriate for examining the question of Piedmont stream recovery need to be developed and tested.

Currently, researchers at Case Western Reserve University are conducting studies in the Murder Creek watershed to improve this sediment budget by replacing the USLE estimates of current erosion rates with direct erosion rate measurements using Cesium 137 techniques (Montgomery et al., 1997). This sediment budget provides direct evidence that bedload can comprise a substantial portion of the total sediment load in sand-bedded rivers. In Murder Creek, bedload comprised at least 22 percent to 35 percent of the total sediment load.

Generations of southeasterners have grown up under the assumption that Piedmont streams naturally featured steep unstable banks and turbid waters, while the reality is that these conditions are a direct long-term (multi-millennial) consequence of poor farming practices. Improving sediment conditions in these rivers will be difficult. The Murder Creek watershed is 82 percent forested yet stream bottoms are sandy and mobile, streambanks are unstable, and turbidity at the average discharge ranges from 15 to 70 nepholometric turbidity units. Opportunities to reduce sediment inputs significantly are limited to the small percentage of row-crop lands (estimated at 2.3 percent of the watershed), the 341 km of unpaved county roads, the unknown mileage of paved roads with eroding ditches or cutslopes, and privately owned unpaved roads. Unpaved roads produce a large amount of sediment per unit area, and sediment production from unpaved roads is relatively easy to alleviate. Watershed improvement efforts should include reduction of sediment delivery from unpaved roads as a priority. This project did not attempt to calculate sediment production from ditch systems along paved roads or unpaved private roads, and these are areas for further investigation.

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