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Channel morphology and sediment origin in streams draining the Georgia Piedmont

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Summary Urbanization is common across much of the US However, the Southeast, including the Georgia Piedmont, is developing much faster than other regions [USDA, NRCS, 2004. Natural resources data and analysis. <http//:www.nrcs.usda.gov/technical/nri_data.html>. State of the Land]. Consequently, water resources in the Middle Chattahoochee Watershed of western Georgia are threatened by increased sedimentation from extensive urban development as well as from other land covers such as livestock grazing and silviculture. A 2-yr study was developed to assess sediment transport and origin across 16 watersheds draining urban, developing, pastoral, managed forest and unmanaged forest landscapes. Total suspended solids (TSS) and total dissolved solids (TDS) yields and sediment rating curves were measured concomitantly with channel morphometry measurements in each stream. Urban streams featured the lowest baseflow concentrations, but sediment concentrations rose rapidly during stormflow in urban streams. Detailed cross-sections assessed channel stability and showed that pasture streams were the most unstable streams during stormflows. Finally, sediment source tracking was performed in a subset of intermittent streams using amorphous to crystalline ratios of iron to estimate the fraction of sediment coming from instream vs. landscape sources. Artificial stormflows were generated to mobilize bed sediment for the development of an instream sediment signature. If these ratios differed during natural events, it was inferred the differences were due to sediments mobilized from the terrestrial landscape. Results indicated that higher ratios of amorphous:crystalline Fe occurred during artificial floods (urban = 0.60 and unmanaged forest = 0.14) than natural stormflows (urban = 0.08 and unmanaged

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Abbreviations: TDS; total dissolved solids; TSS; total suspended solids; FC; fecal coliform; IS; impervious surface.
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forest = 0.03) in watersheds dominated by urban and unmanaged forest land cover, suggesting that crystalline (i.e., terrestrial) sources of Fe were transported to the stream during rainfall events.

Introduction

Urban sprawl and land cover conversion threaten streams throughout the US. Anthropogenic influences such as channelization, land clearing, and impervious surface construction have detrimental impacts on streams and their associated flood plains such as flooding, channel widening, and sedimentation. Direct effects from impervious surfaces such as increased sediment delivery to streams, decreased channel stability, and hydrological alteration can negatively affect biotic habitat and species.

The southeastern US is particularly vulnerable to sedimentation and channel instability from rapidly increasing urban development and the residual alluvium present from the cotton farming era of the early 1900s (Trimble, 1974). Investigations of humid regions of the US have reported that channel instability and reduction in biotic integrity are evident at impervious surface levels as low as 10–20% (Booth and Reinelt, 1993; Schueler, 1995). Impervious surfaces in metropolitan areas such as Atlanta, Georgia, and on a smaller scale, Columbus, Georgia, now compromise more than 50% of the total land cover in many watersheds, thereby threatening ecological sustainability within the Piedmont physiographic province.

Stream morphological assessments typically employ historical comparisons of cross-sections, hydraulic geometry measurements, detailed field surveys, and/or measurements from topographic maps (Gregory et al., 1992). However, impacts of channel morphology on stream biota and their habitats require finer sampling resolutions, such as storm-based morphological assessments. The importance of spate flow events on biotic integrity can be high (Clausen and Biggs, 2000; Helms et al., 2005). Stream organisms can be displaced, injured, or killed during single spate flow events and the substrates they utilize as habitat can be buried or scoured (Power and Stewart, 1987).

In addition to stability issues, conversion of forested to urbanized landscapes often results in increased sediment inputs into streams, which predominately occurs in two phases that have been outlined by Finkenbine et al. (2000). In the first phase, during watershed urbanization (i.e., clearing and construction), stream channels become conduits for fine sediments originating from terrestrial sources (Wolman and Schick, 1967), and entrained sediments are transported downstream or settle and become stored as alluvium (Trimble, 1983; Phillips, 1986). The second phase of sediment transport occurs following development, where impervious surfaces (IS) often cover >50% of the land area within a watershed. Large increases in IS often lead to higher peak flows and more frequent bankfull discharges, thus stimulating channel bed and bank erosion (Finkenbine et al., 2000; Paul and Meyer, 2001). According to the two aforementioned phases of sediment transport, the sediment sources are directly related to terrestrial processes. However, channel redistribution and storage of sediments are also sources of instream suspended sediment (Peart, 1989; Walling et al., 2003).

To determine sediment origin, an array of sediment tracking (i.e., ''fingerprinting'') techniques have been developed. Sediment color (Grimshaw and Lewin, 1980; Phillips and Marion, 2001), mineralogy (Klages and Hsieh, 1975), radiometry (Murray et al., 1993), physical/chemical properties (Peart and Walling, 1986), and isotopic (e.g., strontium) (Douglas et al., 1995) analyses each have been used with success. Typically, these methods are regionally or locally specific (Grimshaw and Lewin, 1980; Walling and Woodward, 1992; Wallbrink et al., 1998; Phillips and Marion, 2001).

The most applicable method available for the Piedmont is the use of Fe oxidation states, as described by Phillips and Marion (2001). They investigated sediment residence times in the eastern Texas Coastal Plain and distinguished between old and new alluvial sediment. In their assessment, Munsell color of sediments was used to differentiate between oxidized and reduced sediment, which provided an estimate of sediment residence times (i.e., reduced sediments have lower chroma than oxidized sediments). Although innovative, this colorimetric approach can be affected by factors other than Fe oxide mineralogy. Thus, we proposed to utilize preferential Fe extraction techniques across two streamflow scenarios (i.e., artificial and natural) to quantitatively characterize Fe oxides as potential source tracking mineral. Applications for selective Fe extraction have been used by Hillier (2001) and Collins and Walling (2002). These studies showed the potential of both oxalate and dithionite-extractable Fe ($\mathrm{Fe}_{\mathrm{ox}}$ and $\mathrm{Fe}_{\mathrm{DCB}}$, respectively) as a useful signature in sediment fingerprinting techniques.

Iron form is generally related to its oxidation state, where crystalline forms are typically more oxidized than poorly crystalline forms of Fe oxides (e.g., ferrihydrite) (Schwertmann and Fischer, 1973). Thus, we hypothesize that instream sources of sediment will include greater quantities of the less crystalline, more amorphous forms of Fe (e.g., ferrihydrite), whereas terrestrial sediments are expected to be dominated by more crystalline forms of Fe such as goethite and hematite. As a result, TSS originating from terrestrial sources will exhibit a low ratio of $\mathrm{Fe}_{\mathrm{ox}}$:$\mathrm{Fe}_{\mathrm{DCB}}$, whereas TSS originating from instream sources will have higher concentrations of poorly crystalline Fe (i.e., $\mathrm{Fe}_{\mathrm{ox}}$) and thus, a higher $\mathrm{Fe}_{\mathrm{ox}}$:$\mathrm{Fe}_{\mathrm{DCB}}$ ratio.

The aim of this study is to investigate the impacts of land cover on perennial streams, and also the headwater processes that control them. More specifically, the objectives are to (1) develop TSS and TDS prediction models based on current land cover and anticipated land cover change; (2) determine sediment source, whether terrestrial or instream, across a land use/cover gradient; (3) assess stream channel aggradation and scour through seasonal and storm-event-based field surveys; and (4) develop storm-based sediment rating curves. Specific land covers compared include urban, developing, pasture (grazed by cattle or hay land), managed forest (predominantly loblolly pine plantations, *Pinus taeda* L.), and unmanaged forest.

Methods

Study area

The Columbus area offered a unique opportunity to investigate the effects of land cover due to its directionally constrained urban development (i.e., the urban development is forced to the north and northeast of Columbus due to Ft. Benning Military Reservation lying along the eastern, southern, and southeastern border of Columbus and the Chattahoochee River/Alabama border restricts growth to the west), its comparative size to other US cities, and the Fe rich soils of the Piedmont. A 3-county study area within the Piedmont physiographic province of western Georgia was investigated along an urban to rural land cover gradient. Ultisols make up the dominant soil order in the study area, which typically have clayey or loamy subsoils and a kaolinitic mineralogy (Soil Survey Staff, 2003). Historical cotton farming has eroded an average of 18 cm of topsoil between 1700 and 1970 leaving clayey subsoil exposed and filling stream channels with alluvium (Trimble, 1974). Upland soils are typically reddish-brown, acidic, and rich in Fe oxides (Parker and Beck, 2003). The most common Fe oxides are generally goethite (α-FeOOH) and hematite (Fe_2O_3), which express brown to red subsoil colors (Shaw, 2001). Other forms of Fe oxides in the Piedmont include the poorly crystalline ferrihydrite ($Fe_5HO_8 4H_2O$), which commonly occurs as an orange flocculent in slow moving streams and drainage ditches, and lepidocrocite (γ-FeOOH), which typically exists as orange concentrations within poorly drained soils.

Watersheds for this study were selected based on current land cover. Headwater watersheds with first third-order perennial streams that drained between ~500 and 2500 ha were used for morphometry analyses and baseflow and stormflow assessments (Strahler, 1952). Uppermost headwaters streams sampled in the sediment origin analysis drained ~20 and 430 ha watersheds that were drained by intermittent streams. Water sampling locations were located at the watershed outlets and were located within 100 km of the city of Columbus, GA (N32.51130 W84.87499).

Land classification

In March or 2003, true color (i.e., 3-band) aerial photographs were taken and processed for each watershed. Details for the image processing methods are explained by Lockaby et al. (2005). The overall classification accuracy for the image processing was 91% for all land covers combined. Watersheds were classified as urban watersheds because of their high proportions of impervious surface (i.e., >5%). Further, extensive ground-truthing determined that cover classified as ''other'' was dominated by exposed bare ground. In the urban and developing watersheds, bare ground represented housing development, and in the managed forest watershed bare ground was a result of clearcut harvesting, site preparation, and dirt roads. Pastoral land cover was dominated by hayland and actively grazed pastures, where cattle typically had stream access. Managed forests were dominated by loblolly pine plantations, where trees were in various rotation stages ranging from clearcut to mature. Streamside management zones (SMZs) were left during harvesting operations; however, logging roads and landing sites contained large proportions of bare mineral soil and had evidence of erosion. Unmanaged forests were dominated by mixed species (hardwoods—conifers) and had only minute proportions of urban development, grazing, or harvesting within the watersheds. It is important to note that several land uses can exist within an individual land cover category, which may result in interactive effects of land cover types on sediment movement. Five land cover classes were supported through ground verification. For example, in developing watersheds many of the subdivisions and new homes being developed were concealed beneath dense tree canopies and obscured in the aerial photographs. Thus ground-truthing along the urban fringe verified their presence, which we believe will impose detectible changes in water quality and hydrology. Additionally, although land cover composition appeared similar between unmanaged and managed forests there were distinct difference on the ground and on the aerial photos. Managed forests had distinct and sharp-edged boundaries whereas unmanaged forests had irregular mixtures of evergreen and hardwood species throughout the forestland.

General TSS characterization

Grab samples were collected biweekly between November and March and monthly thereafter between 1 May 2002 and 3 August 2004 at fixed sampling stations near watershed outlets (Lockaby et al., 1993; Schoonover et al., 2005). During both baseflow and stormflow total suspended solids (TSS) and total dissolved solids (TDS) concentrations ($mg\,L^{-1}$) and yields ($g\,d^{-1}\,ha^{-1}$) were determined. Study watershed outlets also were instrumented with stacked-pole water samplers to collect TSS at various stream stages (Van Lear et al., 1997), which allowed for the development of sediment rating curves for the rising limb of storm events. Sampler fabrication involved fastening bottles to metal fence posts at incremental (30 cm) distances vertically along the poles. Water samples were collected from the stacked-pole samplers following storm events of large enough size to increase stream stage by ~30-cm (i.e., the location of the lower bottle, #1). Bottle numbers were positioned in reference to baseflow for each stream, where bottle #1 was 30 cm above baseflow level and each additional bottle was incrementally spaced higher at 30 cm intervals. The stacked-pole bottles were equipped with a water intake and air expulsion tubes that were positioned facing the current parallel to the water surface. The intake tube was located ~25.4 mm below the air expulsion tube, which allowed a water sample to be collected until the stream stage exceeded the level of the air expulsion tube. Snapshots of TSS concentrations were collected at predetermined stages during the rising limb of storm events and collection elevations were known, thus previously developed discharge-stage rating curves enabled TSS yield calculations (Schoonover et al., 2005).

Channel morphometry

Channel morphometry measurements were recorded within the headwater reaches of each watershed to assess stream bed stability. Within each stream, three fixed cross-sections were surveyed at 3-month intervals, where channel depth measurements were measured at 1-m intervals along each transect. Measurements were confined to straight channel reaches in run habitats to avoid overestimates of channel scour.

A detailed grid analysis was also performed in 10 of the watersheds to assess streambed scour/fill following individual storm events. Two streams from each of the five dominant land covers (i.e., urban, developing, managed forest, unmanaged forest, and pasture) were sampled. Three fixed grids were established in straight reaches and confined to runs (areas between riffles and pools) in each stream. Each grid consisted of five fixed transects spaced 1 m apart perpendicular to the channel. Each transect within the grid was measured at 1 m intervals, which resulted in a layout of 1 × 1 m grid squares. The grids were located near the watershed outlets. Following significant storm events (>2.5 cm of rainfall) each grid was resurveyed to determine scour and aggradation volumes. Benchmark elevations were established and measured each sampling period to account for changes due to equipment setup.

Streambed substrate was classified for each stream using dry-sieving techniques where size classes were characterized according to the USDA guidelines (Soil Survey Division Staff, 1993). Three sediment cores were located randomly within the grid sections to allow comparison of distributions of coarse and fine materials within the stream channels to assess the relationship with aggradation and scour of the stream beds (Leopold et al., 1995). Stream channels that did not have grid sections were also characterized by nine random samples collected within straight channel reaches.

Sediment origin

Artificial event

Artificial flow events were created in headwater streams to suspend and isolate instream TSS that allowed for the development of instream TSS signatures (i.e., composed primarily of amorphous iron). Stream stages was altered very little during the artificial flow event and did not increase to a level that would introduce a significant amount of oxidized bank sediments. Fe analyses were performed on the fine fraction (<.05 mm) TSS and was compared to TSS collected during natural storm events. If differences were detected between the artificial and natural events, then it was inferred that differences were attributable to terrestrial derived sediments.

Artificial streamflow was generated by supplementing flow to intermittent channels with 1500 L of water stored in a water tank. Water samples were collected for TSS in 1 L HDPE bottles at two established stations (sites A and B), which were 10 m apart. The water tank was placed 10 m upstream of site A, and 20 m upstream of site B. The initial water release from the tank was considered the beginning of a flow event, and the entire event lasted approximately 8 min. One pre-event sample was collected at sites A and B, and then at 1-min intervals during the flow event. Stream discharge was also recorded before and after the artificial event at sites A and B using a Marsh—McBirney® flow meter (Rantz, 1982).

Natural event

The first rain event following the artificial flow event was sampled to allow for comparison with the signature developed during artificial events. At site A and site B, stream discharge was measured and six 1-L samples were collected during the rising limb or near the peak of the flow event. Samples were stored at ~4 °C and transported for analysis.

Laboratory methods

TSS and TDS samples

The natural rainfall event samples were analyzed for TSS using a composited sample from six individual 1 L bottles. Samples were collected in individual bottles for transportation purposes, and the 6 L volume was required to make certain that a large enough TSS sample volume was collected for analysis. TSS concentrations (mg L^{-1}) for the artificial event were measured for each sample collected at 1-min. intervals for sites A and B. Further, to ensure that sufficient sediment was available for Fe analyses, water samples for sites A and B for each 1-min. sample within the artificial event were combined. TSS was analyzed using vacuum filtration methods outlined by the US Environmental Protection Agency (1999) and TDS was measured on an Accumet AB 30 (Fisher Scientific, Pittsburgh, PA). TSS yields (kg ha^{-1} d^{-1}) were calculated by first multiplying concentration data (mg L^{-1}) by stream discharge measurements (L s^{-1}) and then dividing the product by the watershed area (ha).

Selective Fe extraction

Suspended sediment samples were flocculated using $MgCl_2$ (solid), allowed to settle for 24 h, and the supernatant was removed by siphoning. Organic matter (OM) was then removed using 30% H_2O_2 in a NaOAc buffer solution adjusted to pH 5 (Jackson, 1969). Once the OM was removed, the samples were washed with deionized water, followed by an ethanol and water (50:50) solution, and then by a final washing with pure ethanol to remove salts. The samples were shaken overnight with 1 M Na_2CO_3 to disperse the soil particles. Sand (0.05—2 mm) was separated from silt and clay (<0.05 mm) by wet sieving, and the fine separates underwent dialysis to remove excess salts. Samples were freeze-dried and weighed prior to analyses.

The pre-treated TSS samples were equally divided. One half of the sample was analyzed using acid ammonium oxalate extraction (in the dark to extract poorly crystalline Fe oxides) (Schwertmann, 1964; Schwertmann et al., 1982). The remaining half of the TSS sample was treated with dithionate-citrate-bicarbonate (DCB) to extract both poorly crystalline and crystalline Fe oxides (Mehra and Jackson, 1960). Following the extractions, Fe was quantified using atomic absorption spectroscopy (AAS). We are assuming that the Fe did not change form (i.e., crystalline vs. amorphous) during the sample collection and analyses processes.

Statistical analyses

Five dominant land cover categories were determined from submeter aerial photographs: urban, developing, pasture (cattle grazing and/or forage production), managed forests (systems with active silviculture), and unmanaged forests (dominated by mixed hardwood stands with little management). Developing land cover was separated from other land covers by evidence of subdivisions and active construction sites. In the statistical analyses, land cover (i.e., managed and unmanaged forest, pasture, impervious surface) proportions were independent variables and the TDS and TSS parameters were the dependent variables. In a subset of the following analyses, land covers were analyzed as categorical variables, and it is necessary to note that multiple land covers were present within all watersheds (Table 1) and consequently, experimental units were not completely homogeneous. To display these data, boxplots were created for TSS and TDS concentrations and yields among land covers that report the mean, median, 75th percentile, 95th percentile, and extreme values. Samples were replicated by time (fixed sampling regime). Statistical separation between urban (i.e., >5% IS) and nonurban (i.e., <5% IS) watersheds was performed using nonparametric Kruskal–Wallis tests.

MAXR regression was used to examine relationships between land cover variables and TSS and TDS (Cody and Smith, 1997). Regression model development is described in more detail by Schoonover et al. (2005). Land cover separations were tested using general linear models with least significant differences for mean separation. To meet normality assumptions of the regression model, dependent variables were log-transformed to fit the normal distribution (Sokal and Rohlf, 2000).

Stream cross-sections were surveyed for depth changes across a perpendicular stream transect. Descriptive statistics were used to illustrate the data. For example, the range provides information on vertical fluctuation of the stream bed, where high ranges depict considerable changes in bed elevation over time, or unstable substrates. Grid data were analyzed by calculating volumetric changes (cm^3) for each 1×1 m grid square and absolute value of change for each surveyed point. These metrics were calculated for each storm event, thus coefficient of variation and mean values could be used to illustrate the data. Absolute values were calculated to provide an estimate of overall bed stability.

Significant differences in extractable Fe among land covers were calculated using ANOVA in SAS (SAS Institute, 1999). Land cover categories were independent variables and total suspended solids (TSS), discharge, and extractable Fe quantities were dependent variables. Pearson linear correlation coefficients were used to test for significant relationships among dependent variables. A probability level of $\alpha = 0.05$ was used for all statistical tests, and SAS Version 8 software was used for all analyses (SAS Institute, 1999).

Results and discussion

TDS and TSS

During baseflow and stormflow, TDS concentrations (mg L^{-1}) and yields ($\text{g ha}^{-1}\,\text{yr}^{-1}$) in urbanized watersheds (IS >5%) were approximately double those ($p < 0.0001$) in all other land covers combined (Figs. 1 and 2). Crippen (1967) reported that dissolved solids increased tenfold following suburban development. Anthropogenic influences, such as urbanization, have been shown to increase TDS levels in receiving waters (Knighton, 1984). Further, field monitoring has shown solute loads to increase in a downstream direction throughout the highly urbanized Bradford catchment is West Yorkshire (Old et al., 2006).

TDS concentration (mg L^{-1}) was significantly explained by the following equation ($r^2 = 0.66$, $p = 0.0052$) derived from MAXR analysis:

$$\log \text{TDS} = -0.06(\text{IS}) - 0.07(\text{M}) - 0.11(\text{E}) - 0.09(\text{P}) + 12.04 \tag{1}$$

where IS is the % impervious surface, M the % of watershed as mixed forest (unmanaged forest), E the % of watershed as evergreen forest (managed forest), P the % of watershed as pasture.

This equation was validated for predictive accuracy based on land cover composition from six test watersheds (Table 1), though TDS concentrations were generally underestimated.

TSS concentrations were not different among land covers although median yields were higher in nonurban watersheds during baseflow conditions, which is likely a result of the several high concentrations in the pasture and unmanaged watersheds (Fig. 1). The elevated TSS yields are likely attributable to differences in stream substrate sizes (Table 2). Critical shear stress is higher for larger particles of sediment (Leopold et al., 1995), thus more energy is required to entrain the larger substrates in urban streams. Channel substrates in urban watersheds were >60% coarse materials (i.e., >1 mm in size), which required ~2× as much energy to entrain particles compared to nonurban substrates, which were predominately <1 mm in size (see Leopold et al., 1995). TSS concentrations were neither explained by a significant land cover based prediction equation, nor were they significantly correlated with hydrology variables or substrate size classes.

Storm sampling

Although there were no significant differences in TSS yields ($\text{t ha}^{-1}\,\text{yr}^{-1}$) among the land covers, a trend in TSS yields was apparent within urban watersheds during stormflow. In urban streams, TSS yields peaked at ~1 m stage (i.e., ~6000 L s^{-1} of discharge), and then declined in subsequent samples (Fig. 3). This trend was not observed in any other land cover category, and was likely attributable to high proportions of impervious surfaces ($\gtrsim$ 25–30%) in the urban watersheds. Additionally, the urban and developing watersheds had higher numbers of samples collected at both 30 cm ($p = 0.0386$) and 90 cm stages ($p = 0.00343$) than all other land cover types. Impervious surfaces contribute copious volumes of quick flow (overland flow) to receiving waters, and thus, stream discharge increases quickly in response to rainfall events (Arnold and Gibbons, 1996; Schoonover et al., 2005). Additionally, the initial flushing of these surfaces supports the observed trend where TSS peaked early in the flow events. Furthermore, the increased

Table 1 Study site characteristics and land cover classification for watersheds used in the study

Land cover category	Stream name	Watershed area (ha)	Stream order	% Impervious surface	% Evergreen	% Deciduous	% Grassland
Sixteen streams assessed for TDS and channel morphometry characterization							
Urban	Lindsay Creek	2546	2[a]	41.9	20.9	12.3	22.7
	Cooper Creek	2496	2	24.9	30.5	15.9	24.9
	Roaring Branch	367	1	30.3	28.4	11.1	27.1
Developing	Standing Boy Creek (tributary 1)	2009	3	1.8	38.6	35.0	20.3
	Standing Boy Creek (tributary 2)	634	2	3.4	37.3	35.4	19.9
	Standing Boy Creek (tributary 4)	2659	3	3.3	41.2	22.8	27.6
Pasture	Mulberry Creek (tributary 1)	1178	3	3.7	29.3	24.	36.8
	Wildcat Creek (tributary to Flat Shoals Creek)	2420	2	2.5	32.8	29.0	33.2
Managed forest	Cline's Branch (tributary to Mountain Oak Creek)	897	2	1.5	48.3	33.0	13.0
	House Creek	655	2	1.3	47.8	26.7	19.6
	Mulberry Creek (tributary 2)	606	2	2.6	42.4	25.0	16.5
	Sand Creek	896	2	1.2	44.8	28.8	20.8
Unmanaged forest	Beech Creek	647	2	2.3	46.6	34.1	13.2
	Blanton Creek	364	1	1.2	48.1	28.2	18.6
	McKoon Creek	663	2	2.3	36.4	37.9	19.8
	Mulberry Creek (tributary 3)	1044	2	1.9	41.6	37.1	14.8
Six streams used for testing TDS prediction model							
	Blue Springs Branch	697	1	1.7	47.4	36.3	14.0
	Five Points West Branch	489	2	1.0	40.3	36.9	19.9
	Flat Shoals (tributary 5)	1183	2	1.1	46.3	36.1	15.2
	Flat Shoals (tributary 6)	922	2	0.7	48.0	24.7	24.8
	Weracoba Creek	2193	2	49.5	22.2	10.2	12.9
Eight subwatersheds used for the sediment origin assessment							
	Lindsay Creek		Int.[b]	37.1	23.9	13.5	23.4
	Cooper Creek		Int.	17.3	33.8	19.8	22.8
	Standing Boy Creek (tributary 1)		Int.	2.8	33.6	33.3	22.8
	Standing Boy Creek (tributary 4)		Int.	3.7	54.74	18.7	20.8
	House Creek (tributary 2)		Int.	1.64	30.47	22.22	43.95
	Mulberry Creek (tributary 1)		Int.	1.7	12.2	14.9	66.2
	Mulberry Creek (tributary 2)		Int.	3.5	40.0	26.0	17.9
	Beech Creek (tributary 2)		Int.	2.6	47.9	33.8	13.4

[a] Stream order was calculated from perennial streams designated on USGS 7.5' Quadrangle maps using the Strahler classification system (Strahler, 1952).

[b] Int. = Intermittent stream.

discharges could entrain channel substrates and result in increased TSS. Once discharge exceed 6000 L s^{-1} of discharge in urban streams, the data suggest that the contributing runoff was much cleaner or diluted, in terms of TSS, than during the earlier contributions of runoff. The rapid increase in pollutant yields followed by subsequent dilution has been commonly observed in urban channels and was described as the ''first flush phenomenon'' (Deletic, 1998; Lee

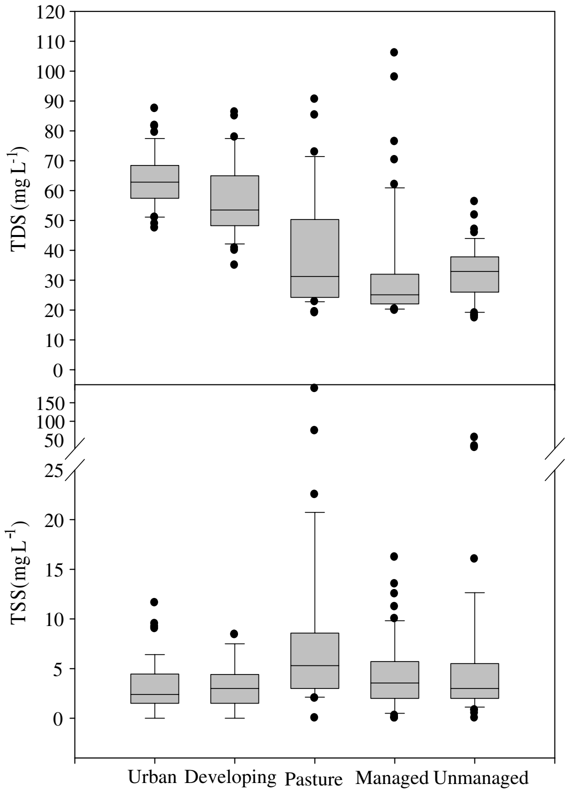


Figure 1 Boxplots illustrating total suspended solid (TSS) and total dissolved solid (TDS) concentrations (mg L^{-1}) in the 16 west Georgia watersheds. The solid line within the box represents the median, the dotted line is the mean, the box ends are the 75th percentile, the whiskers represent the 95th percentile, and the dots represent extreme values.

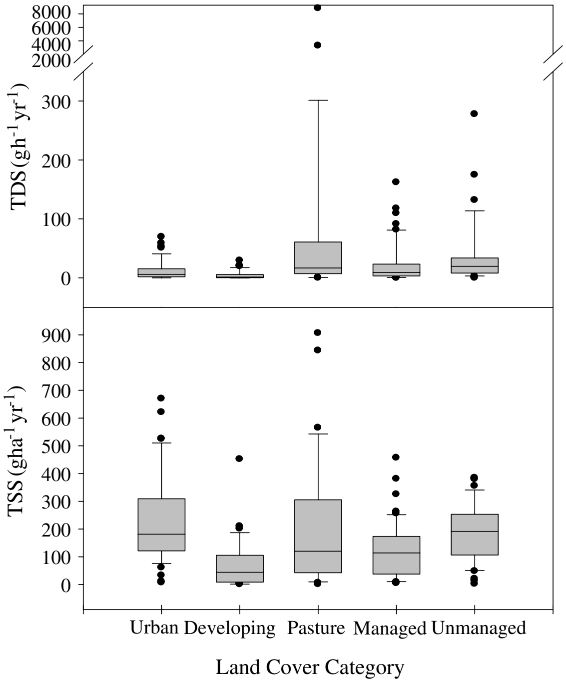


Figure 2 Boxplots illustrating total suspended solid (TSS) and total dissolved solid (TDS) yields (g ha^{-1} yr^{-1}) in the 16 west Georgia watersheds. The solid line within the box represents the median, the dotted line is the mean, the box ends are the 75th percentile, the whiskers represent the 95th percentile, and the dots represent extreme values.

et al., 2002; Soller et al., 2005). However, not all urban catchments support the first flush phenomenon (Lawler et al., 2006).

Streams draining areas with high proportions of impervious surfaces displayed frequent fluctuations in discharge. The total number of events that filled bottles at stage levels between 30 and 90 cm was correlated positively with the frequency of stream discharges exceeding 3×-, 5×-, and 7×-median flow ($r = 0.54$, $p = 0.04$; $r = 0.68$, $p = 0.01$; $r = 0.64$, $p = 0.01$, respectively) (Schoonover et al., 2005).

Surprisingly, watersheds with large proportions of unmanaged forests had some of the highest yields of TSS in the stacked-pole samplers. As stream stages rose, TSS yields increased considerably throughout the events, this trend was also evident in managed forest watersheds (Fig. 3). The trend that the forested watersheds portrayed was much different than urban watersheds that were diluted as stage increased beyond the first flush effect. Studies have reported high sediment losses associated with unpaved forest roads (50–90 t ha^{-1} yr^{-1}), skid trails and logging decks (25 and 101 t ha^{-1} yr^{-1}, respectively), and harvesting (39% increase of TSS compared with unmanaged natural forest) (Grayson et al., 1993; Stott et al., 2001; Wallbrink et al., 2002). In the Piedmont of Georgia, Hewlett (1979) attributed 90% of the mass loss of sediment to poor harvesting practices, such as poorly designed roads and land disturbance by equipment. Much of the rural Georgia landscape in the study area commonly had dense networks of unpaved roads, particularly in the forested areas.

Pastoral streams had much lower yield increases than other watersheds; however, they followed the trends of increasing TSS production during runoff events (Table 3), such as in the forested watersheds. TSS yields in developing watersheds were slightly higher than all other land covers early on the rising limb of the storm hydrographs (Table 3). Developing watersheds also experienced flashy responses to rain events (Schoonover et al., 2005), which potentially entrained bed sediments during the initial runoff period. The primary difference between the channels in urban and developing lands was the substrate size. Extensive scour in the lower reaches of the urban channels has led to coarser, more resistant substrates than in the developing watersheds. It is likely that the finer substrates in developing watersheds were entrained during the flow pulses in response to rainfall, which ultimately produced higher TSS yields.

Event mean concentrations (EMCs) (Novotny, 2003) for TSS were calculated for each watershed. No significant correlations between EMC and land cover proportions were evident. However, dominant land covers were significantly different based on categorical comparisons in Table 3 ($p = 0.0082$). Pastured watersheds contributed the lowest median EMC TSS compared with all other land covers. Developing, unmanaged forest, managed forests, and urban

Table 2 Substrate particle size classes within 16 study watersheds surveyed in west Georgia

Particle size (mm)	Land cover category				
	Urban (3)	Developing (3)	Pasture (2)	Managed (4)	Unmanaged (4)
Proportion of substrate within particle size classes (USDA classification)					
>2	0.52	0.33	0.10	0.28	0.16
1.0–2.0	0.16	0.33	0.019	0.19	0.14
0.5–1.0	0.21	0.22	0.42	0.30	0.37
0.25–0.5	0.09	0.09	0.26	0.18	0.28
0.053–0.25	0.02	0.02	0.03	0.04	0.04
<0.053	0.0008	0.002	0.004	0.005	0.002

Numbers in parentheses represent the number of watersheds in each category.

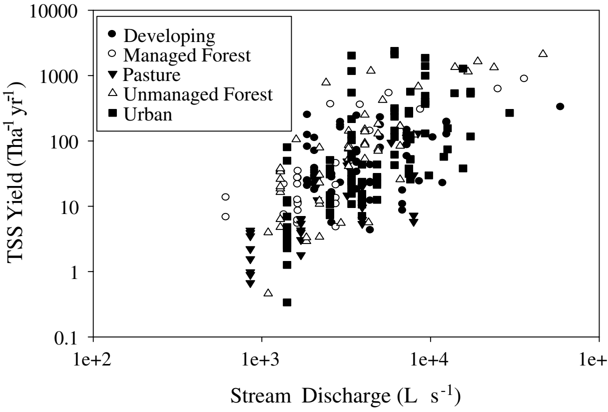


Figure 3 Log–log plot of sediment rating curves based on stacked-pole samples, discharge (L s^{-1}) is plotted vs. total suspended solid (TSS) yields (t ha^{-1} yr^{-1}).

watersheds were not significantly different from one another. However, observed EMCs of TSS in urban watersheds were considerably higher (474 vs. 69–101 mg L^{-1}) than those of residential and commercial uses reported by the EPA (1983) in nationwide urban runoff program (NURP) sites.

Cross-section morphometry

Aggradation, scour, and streambed stability were assessed using stream cross-section measurements at three month intervals (Table 4). Two stream sampling locations were lost and, as a result, data are based on 16 watersheds. Aggradation and scour were calculated by averaging positive and negative changes along a cross-section transect. From 10 January 2003 to 16 May 2003, streams draining managed forests showed significantly greater channel scour than both urban and unmanaged forest land covers (Table 4). No other significant differences were observed for individual sampling periods or the overall mean, median, or range values. However, between the date of cross-section installation (i.e., initial sampling date) and the final sample date, pastoral and managed forests experienced greater scour than the other land covers. On average, no land cover was subjected to net accumulation of sediments in the headwater reaches, which suggests that channel erosion or stream conveyance of legacy sediment may be greater than terrestrial inputs.

Streambed stability was much more variable among land covers than estimates of channel scour and aggradation (Table 4). Scour and aggradation were computed to serve as an indicator of biotic stress among land covers (Helms et al., 2005). Within the same west Georgia streams, Helms et al. (unpublished data) documented increases in tolerant

Table 3 Stacked-pole TSS yields (t ha^{-1} yr^{-1}) and event mean concentrations (EMCs, mg L^{-1} ± 1 SE) across the five dominant land covers in west Georgia, USA

Bottle stage level (cm)	Urban (3)[A]	Developing (3)	Pasture (2)	Pine (4)	Mixed (4)
30	10.6 (33)[B]	27.3 (20)	3.1 (10)	8.5 (9)	18.6 (9)
60	38.7 (24)	44.2 (14)	6.3 (10)	12.4 (7)	22.9 (5)
90	50.3 (10)	77.7 (9)	8.4 (4)	13.2 (5)	75.8 (5)
120	261.0 (7)	125.3 (5)	30.0 (3)	353.9 (3)	138.8 (5)
150	148.9 (2)	175.1 (2)	112.7 (1)	707.7 (2)	75.1 (3)
180	74.3 (2)	–	130.4 (1)	–	168.3 (3)
210	–	–	–	–	124.1 (1)
EMC	474.0 ± 109.3 a[C]	652.6 ± 90.0a	125.3 ± 126.2b	297.7 ± 225.0ab	690.8 ± 141.0a

[A] Number of watersheds sampled in the land cover category.

[B] Number in parenthesis represents the number of samples collected at the respective bottle location (stage levels are in relation to average baseflow).

[C] Within row, different letters represent significant differences at α = 0.05.

Table 4 Mean (±1 SE) and absolute value (±1 SE) change in cross-section depth (cm) by dominant land cover

Parameter	Land cover				
	Urban	Developing	Pasture	Managed	Unmanaged
Mean (cm) (±1 SE)					
1/10/03–5/16/03[A]	−0.76 ± 0.85a[B]	–	–	−7.68 ± 1.86b	−0.70 ± 0.85a
5/16/03–7/29/03	−1.55 ± 0.76a	0.85 ± 0.52a	−1.28 ± 1.58a	−0.55 ± 0.73a	−0.64 ± 0.76a
7/29/03–1/12/04	−0.24 ± 0.94a	0.15 ± 0.76a	1.13 ± 2.23a	0.18 ± 0.79a	−1.68 ± 0.94a
1/12/04–3/18/04	−0.88 ± 0.73a	−1.89 ± 0.82a	−2.01 ± 0.94a	−0.88 ± 0.88a	1.04 ± 0.73a
3/18/04–6/9/04	1.49 ± 0.49a	0.00 ± 0.61a	1.01 ± 0.64a	0.64 ± 0.64a	0.76 ± 0.49a
Mean	−0.79 ± 0.24a	−0.24 ± 0.12a	−0.40 ± 0.91a	−0.91 ± 0.40a	−0.21 ± 0.24a
Median	−0.55 ± 0.21a	0.00 ± 0.18a	−0.70 ± 0.94a	−0.91 ± 0.40a	−0.37 ± 0.21a
Range	11.5 ± 1.40a	11.1 ± 1.34a	11.4 ± 2.53a	15.0 ± 1.58a	11.1 ± 1.40a
Maximum aggradation	39.32	29.9	43.6	50.6	29.6
Maximum scour	−36.9	−37.8	−27.7	−63.1	−35.4
1/10/03–6/9/04	0.00 ± 1.10a	−0.09 ± 0.61a	−4.75 ± 2.41b	−4.39 ± 1.10b	−2.26 ± 0.85a
Absolute values (cm) (±1 SE)					
1/10/03–5/16/03	1.74 ± 0.37b	–	–	9.20 ± 1.71a	3.63 ± 0.61b
5/16/03–7/29/03	5.67 ± 0.70a	3.26 ± 0.40bc	6.80 ± 1.13a	4.72 ± 0.55b	3.93 ± 0.61c
7/29/03–1/12/04	4.45 ± 0.64a	3.93 ± 0.64a	6.86 ± 1.83a	4.48 ± 0.64a	4.48 ± 0.82a
1/12/04–3/18/04	3.35 ± 0.34a	4.05 ± 0.70a	3.47 ± 0.76a	4.30 ± 0.79a	3.20 ± 0.67a
3/18/04–6/9/04	3.66 ± 0.52a	3.23 ± 0.52a	2.16 ± 0.46a	2.77 ± 0.58a	2.41 ± 0.43a
Mean	2.07 ± 0.21a	0.76 ± 0.12c	2.99 ± 0.76a	1.77 ± 0.37b	1.25 ± 0.21bc
Median	2.16 ± 0.21b	0.91 ± 0.15c	3.38 ± 0.76a	1.71 ± 0.37b	1.22 ± 0.18c
1/10/03–6/9/04	7.32 ± 0.76b	3.72 ± 0.46c	12.5 ± 1.46a	6.61 ± 0.94b	4.54 ± 0.70bc

Positive and negative numbers represent aggradation and scour, respectively.

[A] Average scour (−) or aggradation (+) for sampling period.

[B] Within rows, different letter represent significant differences ($\alpha = 0.05$).

species (e.g., Chironomidae) in streams having low bed stability (unpublished data). Morphology data suggested that unmanaged forests and developing watersheds were the most stable systems during each of the individual sampling periods, overall, and between the initial and final measurements. Pasture and urban watersheds had the lowest stability during the first half of 2003 and during the overall study period. As the proportion of pasture (x) increased in a catchment, the habitat stability (y) decreased ($y = 0.40x - 4.04$, $p = 0.0005$, $r^2 = .60$). Watersheds dominated by managed forests experienced intermediate disturbance levels in terms of habitat stability.

Stream substrate sizes were correlated with habitat stability. As the proportion of particles between 0.5 and 1.0 mm increased, bed stability suggested a weak inverse trend ($r = -0.47$, $p = 0.0683$). Pasture and managed forest streams had a large proportion of sediments in this size-class. Conversely, particle sizes greater than >2 mm, which were more common in developing and unmanaged forest watersheds, were correlated positively with increased stability ($r = 0.58$, $p = 0.0177$). Urban streams also had a large proportion of coarse materials.

Streambed grid analysis

Ten stream channels were sampled using grid sections near the watershed outlets (Table 5). Similar to the cross-sections, data were analyzed by overall change (cm^3) (for each grid square) and the absolute value of overall change ($|\text{cm}^3|$) (for each survey point). The absolute value was used to estimate overall stability due to alterations between aggradation and scour among storm events was evident for each sampling point. For example, a single grid cell may experience 10 cm of sediment accumulation during a storm event and that same point during a subsequent event may have 11 cm of substrate scoured away, thus long term analyses would suggest that 1 cm of the bed was lost, whereas the absolute value storm-based movement will provide a stability indication for each positive and negative fluctuation in the substrate elevation.

Urban, developing, and pastoral streams are scouring, whereas the two forest types were accumulating sediments or remaining relatively stable. The absolute values of change also support the trend, where urban and developing watersheds have the lowest stability in terms of volume change.

Data from the headwater cross-sections and the grids suggest that the unmanaged forests have stable stream channels. However, the cross-sections in developing watersheds were stable as well, but the grids were not. Cross-section measurements were commonly recorded in headwater sections of developing streams that are upstream of housing developments, thus they were less susceptible to sedimentation and hydrologic alteration. The headwater reaches of developing watersheds closely resemble those of unmanaged forests despite the downstream differences.

Pastoral watersheds were unstable according to both the cross-section and the grid data. In both instances, scour was high and overall habitat stability was low. Hydrology also was monitored throughout the study, and baseflow values

Table 5 Storm-event-based volumetric change (cm^3) and absolute change data for grid cross-sections in 10 watersheds from each dominant land cover

Parameter	Change vs. Stability	Land cover				
		Urban (2)[A]	Developing (2)	Pasture (2)	Managed (2)	Unmanaged (2)
Average	Change (cm^3)	−849 ± 1342a[B]	−2117 ± 1273a	−3223 ± 1216b	−746 ± 708c	1754 ± 1130c
	Absolute change	40,352 ± 964a	39,947 ± 907a	29,776 ± 822b	20,676 ± 507b	16,589 ± 817b
Median	Change (cm^3)	−2500	−1250	−2500	0	−1250
	Absolute change	26,250	25,000	21,250	12,500	10,000
Maximum	Change (cm^3)	200,000	197,500	110,000	98,750	13,750
	Absolute change	200,000	200,000	110,000	100,000	93,750
Coefficient of variation	Change (cm^3)	−6830	−2686	−1246	−3968	1363
	Absolute change	103	101	91	102	104

[A] Number in parenthesis represents the number of watersheds sampled.
[B] Within rows, different letter represent significant differences ($\alpha = 0.05$).

were at least four times higher in pasture watersheds than any other land cover (Schoonover et al., 2005). A combination of high baseflow and a sand-dominated substrate probably resulted in the high continual bed movement within the channels, and were particularly important to reducing habitat stability.

Stability issues seen in present-day Piedmont streams are probably an artifact of poor farming practices during the late 1800s and early 1900s (Jackson et al., 2005). Estimates of historic surface soil loss in the Piedmont during the cotton farming era range from 12.2 cm (Jackson et al., 2005) to 18 cm (Trimble, 1974) with an accumulation of 1.6 m in some floodplains (Jackson et al., 2005). Thus, as suggested by Jackson et al. (2005), streambank stability, mobility of sandy streambeds (e.g., pastoral streams in the current study), and turbid conditions in present-day Piedmont streams are probably a legacy effect of the alluvium-rich floodplains created during the cotton farming era.

Sediment origin

TSS and discharge

Land cover classification results and watershed locations for the sediment origin facet of the study are located in Table 1. Stream discharge was significantly higher during natural storms than the artificial flooding for all land covers except unmanaged forest (Fig. 4). High evapotranspiration in the unmanaged forest watershed likely caused the lower observed stream discharges during the natural storm event (Bosch and Hewlett, 1982). Urban streams had significantly higher TSS concentrations during the artificial events than natural events ($p = 0.0005$), which was likely due to the first flush phenomenon previously discussed. This trend was also evident in the stacked-pole data collected from the rising limb of storm events (at 30 cm intervals) in urban streams. The collection schedule for natural events prevented sampling during the first flush of storm events, thus a combination of the first flush and dilution of TSS likely occurred in the urban channels.

Pasture and managed forest streams had the highest TSS concentrations (Fig. 5), which appear to peak early in the flood event (Fig. 6). Urban, developing, and unmanaged forest streams had relatively uniform and low TSS concentrations throughout the events. TSS concentrations declined in the latter part of the artificial flood events in all streams, suggesting the first flush phenomenon may occur to varying degrees across all land covers in small watersheds.

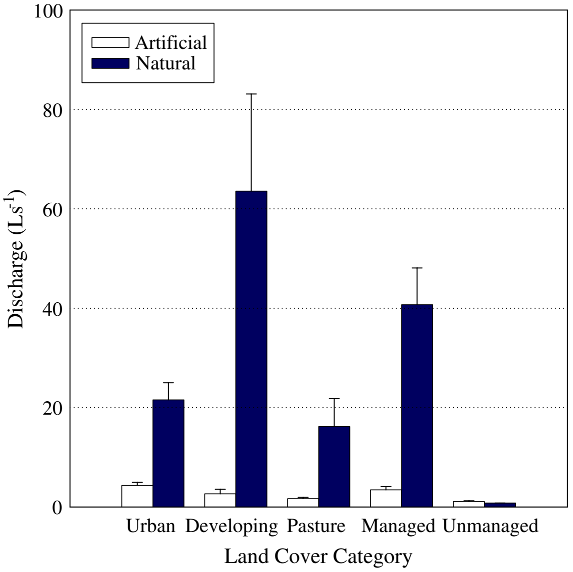


Figure 4 Mean (±1 SE) stream discharge ($L\,s^{-1}$) during artificial and natural stormflow for eight Piedmont streams across a land cover gradient in west Georgia.

Extractable iron

Extractable Fe and Fe_{ox}:Fe_{DCB} ratios in TSS collected during artificial flows were used to develop a signature for in-stream sources of sediment. In both urban and unmanaged forest streams the Fe_{ox}:Fe_{DCB} ratios were significantly higher during artificial flow events than natural flow events ($p = 0.0117$ and $p = 0.0050$, respectively) (Fig. 7). High Fe_{ox} proportions during the artificial flows were expected because oxalate extracts poorly crystalline forms of Fe,

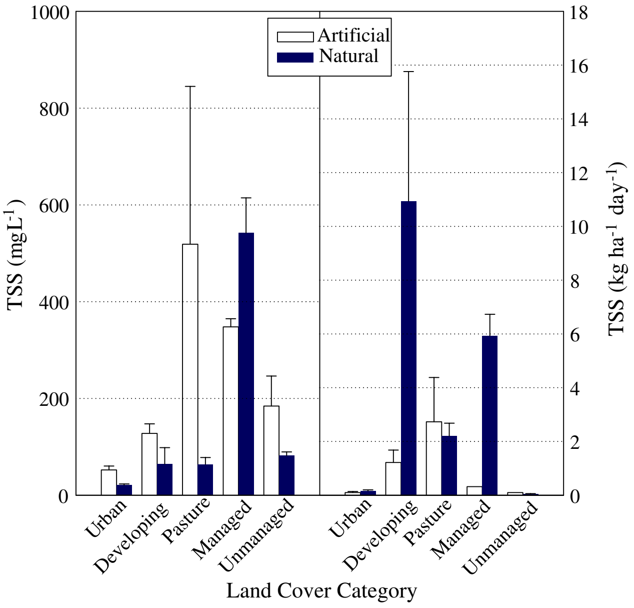
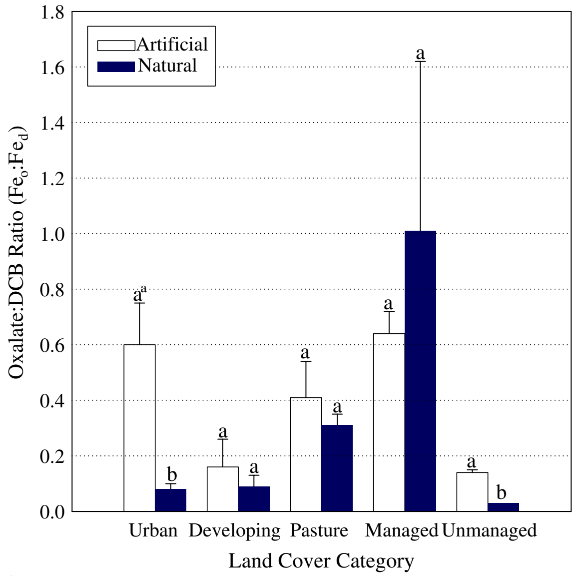


Figure 5 Total suspended solid (TSS) concentrations (mg L^{-1}) (left side of graph) and loads (kg ha^{-1} d^{-1}) (right side of graph) for eight watersheds across an urban—rural gradient in west Georgia ($n = 2$ for each land cover class).



[a]Within land cover, different letters represent significant differences at α=0.05

Figure 7 Mean (±1 SE) Fe oxalate:Fe citrate dithionite (Fe_{ox}:Fe_{DCB}) ratios of suspended sediment fraction <0.05 mm across a land cover gradient in eight Piedmont streams of west Georgia ($n = 2$ for each land cover class).

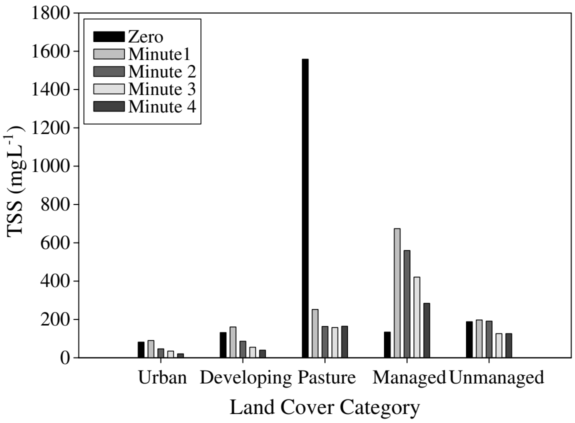


Figure 6 TSS concentrations (mg L^{-1}) (averaged for sites A and B) for eight watersheds during artificial flood events in west Georgia. Time zero represents the concentration of TSS when the initial pulse of discharge reaches the respective site, and subsequent collection times were at 1-min intervals after the time zero collection ($n = 2$ for each land cover class).

which is likely of higher proportion in stream environments. Rhoton et al. (2002) suggest that Fe_{ox}:Fe_{DCB} ratios greater than 0.50 indicated the presence of ferrihydrite, which was the case in our urban and managed forest streams. Further, Shaw (2001) reported low Fe_{ox}:Fe_{DCB} ratios (0.02—0.09) for highly weathered upland ultisols of the Piedmont region thus, low Fe_{ox}:Fe_{DCB} ratios in TSS may suggest contributions from terrestrial sources of sediment. In urban streams the ratio was significantly lower during natural flows (<0.50), suggesting that there was little instream contribution of Fe and terrestrial inputs increased during natural stormflow. Moreover, the Fe_{ox}:Fe_{DCB} ratios decreased from 0.60 to 0.08 in the urban streams and from 0.14 to 0.03 in the unmanaged forest streams between the artificial and natural flows, and the ratios for natural storm events (i.e., 0.08 and 0.03) fall within the range of Fe_{ox}:Fe_{DCB} ratios for terrestrial uplands (0.02—0.09) (Shaw, 2001). Conversely, the managed forest streams Fe_{ox}:Fe_{DCB} ratios did not significantly deviate between the flow regimes, suggesting similar sources of sediment. Further, higher proportions of Fe_{DCB} were evident during natural flows in urban and unmanaged streams, suggesting the presence of more crystalline bound Fe. Terrestrial inputs of sediment appeared to be common in both urban and unmanaged forest watersheds during natural flows because the channels transported TSS enriched with greater proportions of crystalline Fe. By contrast, Fe_{ox}:Fe_{DCB} ratios from developing, pastoral, and managed forest's did not differ significantly during natural flows compared to the artificial flows, suggesting that instream redistribution or scour was the dominant source of sediment.

The prevailing transport mechanism of sediment in urban landscapes was probably overland flow draining impervious surfaces. Higher runoff velocities facilitate soil erosion from bare ground and transport sediments over the impervious surfaces. Additionally, impervious surfaces often accumulate dust and other particles (Schueler, 1995). By contrast, terrestrial sources of sediment in unmanaged forest streams could potentially be related to the amount of land disturbance by wildlife activity, for example, white-tailed deer (*Odocoileus virginianus*). In the unmanaged forest areas (predominately mixed hardwoods) heavily used white-tailed deer stream crossings were common. Unpaved roads within the forested watersheds may have also contributed to the elevated terrestrial inputs.

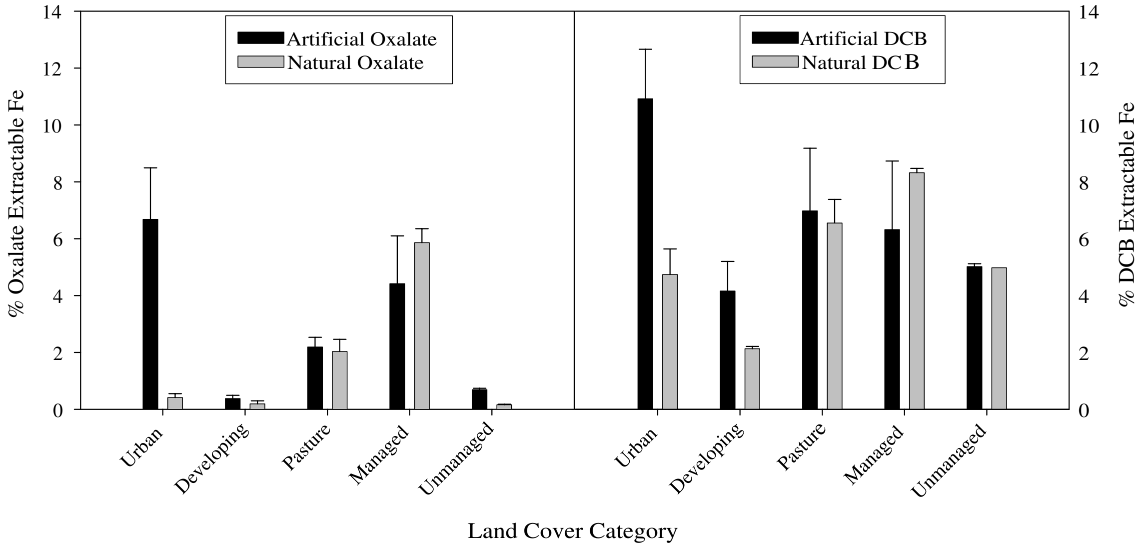


Figure 8 Mean (±1 SE) oxalate extractable Fe (left side of graph) and citrate dithionite extractable Fe (right side of graph) of suspended sediment fraction <0.05 mm across a land cover gradient in eight Piedmont streams of west Georgia.

In contrast to the high sediment yields collected from the stacked-pole samplers in the urban and unmanaged streams near the watershed outlets, they transported low sediment yields compared to those of developing, pastoral, and managed systems in the upper, intermittent reaches of the watersheds. In urban streams, low TSS yield may have been an artifact of the first flush phenomenon, in which the majority of sediments were transported during early stages of storm hydrographs. Whereas, the morphometry analyses of headwater reaches within the unmanaged streams showed stable headwater channels compared to other land covers, which supports the observed low instream contribution of sediment.

Streambed stability also plays an important role in the observed trends. For example, Fe_{ox}:Fe_{DCB} ratios suggest that pastoral streams are dominated by instream sources of sediment, and previous investigations of perennial pastoral channels showed that low bed stability was common. Pasture substrates were predominately composed of fine sands (0.5—1.0 mm) that proved to be highly mobile with high baseflow discharges. Furthermore, stability data for developing watersheds suggested that channel scour was evident, which also suggests that instream sediment sources would be probable. Conversely, managed watersheds were relatively stable in their lower reaches although active headcut movement was observed in channel reaches upstream of TSS sampling locations, where cross-sections showed the greatest scour (Table 4).

During artificial flow, urban streams exhibited higher Fe_{ox} and Fe_{DCB} percentages than all other land covers (Fig. 8). Furthermore, the urban Fe_{ox} and Fe_{DCB} percentages were also higher during artificial than natural stormflow. TSS in the unmanaged forest stream also had a higher percentage of Fe_{ox} during artificial flow, which suggests that the instream signature was composed of a greater proportion of poorly crystalline forms of Fe.

Correlation between land cover proportions and dependent variables were not significant, with the exception of a positive correlation between % evergreen vs. % Fe_{DCB} during natural flow ($r = 0.71$, $p = 0.05$), which may reflect high TSS concentrations during natural stormflow in the managed systems. The lack of additional significant trends may have been due to the relatively small sample sizes.

Conclusions

Although there was a considerable degree of variation, land cover was related to sediment movement and stream channel stability. Historic land use/cover and altered hydrology from contemporary land cover are the most probable influences on channel substrate, which appeared to directly impact bed stability. Contemporary land cover also explained 66% of the variation in TDS concentrations, but did not explain TSS.

Stream stability was variable across the land cover gradient. Physical stream habitats were continually changing in urban, developing, and pastoral landscapes and, thus, organisms could potentially be replaced by species with greater tolerance to habitat modification. However, shifts towards more tolerant species (e.g., Chironomidae) have already occurred in streams that experienced low bed stability, and this may be due to historical sedimentation from farming. Perhaps, biotic diversity in historically disturbed streams would benefit by establishing habitats that resemble pre-disturbed streams. Consequently, restoration and management efforts must consider historic as well as current land cover conditions.

Extractable Fe data suggest that both urban and unmanaged forest landscapes produced higher terrestrial inputs of sediment than all other land covers. Although sediment inputs to streams were relatively low, the potential mechanisms of terrestrial transport were via impervious surfaces and possibly deer trails. However, the degree to which these disturbances (i.e., impervious surfaces and white-tailed deer) contribute terrestrial inputs of sediment is speculative.

The unique application of using Fe and two flooding regimes provides a foundation for the advancement of sediment source tracking methodologies. Future applications of these methods should be based on a more rigorous sampling regime, where natural events are sampled multiple times during each event and, automated samplers are used to capture the first flush.

Individual land covers were treated as categorical variables for a subset of analyses in this study. Thus, it is important to reiterate that the watersheds were composed of various land covers, and that complex interactions of land cover types can be undetected in categorical analyses. Sediment source tracking is critical for effective management of stream ecosystems. Knowledge of sediment sources will allow land managers to effectively develop restoration designs and to direct economic resources to areas that are most susceptible to erosion.

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