HYDROLOGIC INFLUENCE ON SEDIMENT TRANSPORT OF LOW-GRADIENT, FORESTED HEADWATER STREAMS IN CENTRAL LOUISIANA

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Abstract—Extensive research has been conducted on headwater streams in regions with high topographic variation. However, relatively few studies have examined low-gradient headwater stream systems, such as those existing in much of the southeastern Coastal Plain. The focus of this study is to investigate spatial and temporal variation of headwater stream hydrology in a low-gradient forested watershed and determine their effect on the transport of suspended and dissolved sediment. Stream discharge and sediment loads were monitored from December 2005 to April 2007 throughout a central Louisiana third-order watershed, with stream channel slopes of <1 percent. The study found that headwater streamflow in this low-gradient forested watershed was highly variable, from intermittent/no-flow conditions in the late summer, to high-volume overbank conditions in the winter. Transitioning from the headwater streams to the watershed outlet, stream hydrologic response and streamflow variability decreased. Suspended and dissolved solid concentrations during baseflow showed minimal seasonal variation, and loading was mainly controlled by discharge levels. Sediment yield from the watershed was low, due in part to the below normal precipitation and subsequent low storm runoff. As most of the land use in the watershed is commercial forest management, the low runoff decreases erosion susceptibility from harvesting activities. However, caution must also be taken and full implementation of forestry best management practices is recommended as harvest sites can become quickly saturated following precipitation events, creating the potential for unchecked surface runoff and sediment delivery to streams.

INTRODUCTION

Headwater streams comprise over 77 percent of all streams in the United States, encompassing almost half of the total stream length (Leopold and others 1964). Contributing an estimated 70 percent, their contribution and importance to hydrological processes and water quality in all watersheds are considerable. Although forested headwaters have been intensively studied for over a century, few studies exist on the unique processes of low-gradient meandering streams in the southeastern Coastal Plain in the United States. This gap in research and knowledge is especially important, as forests cover approximately 55 percent of the land cover in the Southeast (Flather and others 1990), occupying a large portion of headwater areas. The region has low average land slope and very low-channel slopes, creating extensively meandering streams with very low velocities and seasonally inundated backwaters.

Complexities created by the low-gradient topography and locally elevated ground water located on the Coastal Plain headwaters can make the quantification of sediment yield difficult. Assessment of sediment delivery to streams in this region is critical, however, as it is the primary pollutant to streams from forest-dominated land (Patric and others 1984). During high-flow periods, overbank flooding and reconnection of backwater channels and oxbows complicates in-channel sources and sinks of sediments. Additionally, locally minor variations in topography and large woody debris create complex channel velocities, affecting individual site sedimentation characteristics (Hupp 2000).

In their review of several coastal forested watershed studies, Amatya and others (2005) commented on the limited number of hydrology and water budget studies in these complex and complicated areas and expound on the need for long-term ecohydrologic monitoring to more fully determine the effects of forest management on water quality. In this study, we established a relatively long-term experiment in a low-gradient, forested watershed on the Louisiana Coastal Plain region to determine timber harvest effects on surface hydrology and water quality. In this paper, we analyze data collected from the first 2 years and discuss hydrologic effects on sediment concentrations and loading in this headwater region.

METHODS

Site Description

Located in northcentral Louisiana (fig. 1), the Flat Creek watershed has a drainage area of 369 km^2 and is characterized by relatively flat, low sloping forest land and pasture. Elevation ranges from 24 m at the southern outlet to a high of 91 m in the northern uplands. The long-term (1971 to 2000) average annual temperature in the area was 17.9 °C, ranging from 7.2 °C in January to 27.5 °C in July, and the long-term average annual precipitation was 1508 mm with a low of 90.7 mm in September and a high of 157.7 mm in December (National Climatic Data Center 2002). Soils in the area mainly consist of the poorly drained Guyton (silt loam) series along the Flat and Turkey Creek flood plains, with moderately well drained Sacul-Savannah (fine sandy loam) soils in the upland areas.

Analyzing a LandSat-5 TM image from May 16, 2006, shows evergreen forests dominating land cover with 51.4 percent, followed by deciduous forests at 32.6 percent, recovering harvested areas (1 to 3 years) at 7.0 percent, recently

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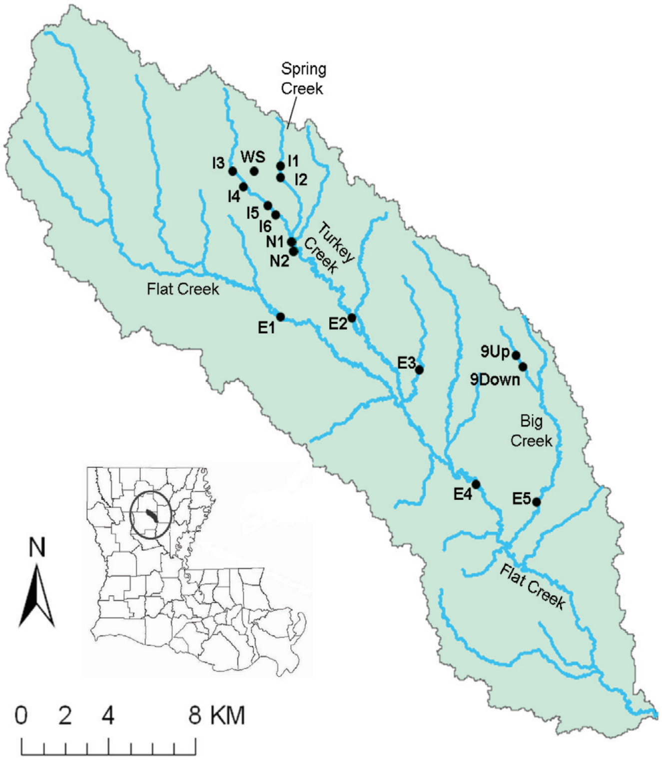

Figure 1—Geographical location of Flat Creek watershed in Louisiana.

harvested areas (<1 year) at 5.0 percent, pasture at 3.9 percent, and surface water making up the final 0.1 percent. A number of county and local dirt roads exist throughout the area. These roads may be significant sources of stream sediment, particularly where they cross or are adjacent to streambeds (Jones and others 2000). Beaver dams are also prevalent throughout the stream network and have been found to be particularly frequent along Turkey Creek.

Field Measurements and Sampling

Automatic samplers were installed at six sites (I1 to I6, fig. 1) along two first-order streams to collect stormwater samples and record stream level. The samplers recorded stream level in continuous 15-minute intervals from December 2005 to April 2007 and were also used to collect storm event water samples to determine effects on stream sediment loading. Programmed to start sampling at a 0.5-foot rise in stream level, the samplers collected 400 mL samples hourly for a period of 20 hours (20 times 400 mL = 8 L composite sample), which were then reduced to 1000 mL unfiltered and 500 mL filtered samples. Baseflow and stormflow 500 mL samples were filtered with a 47-μm glass fiber filter (GF/F) (Whatman International Ltd., Maidstone, UK). The 500-mL and 1000-mL samples were analyzed for total dissolved solids (TDS) and total suspended solids (TSS), respectively, by the Louisiana State University AgCenter Chemistry Laboratory (Baton Rouge, LA). Samples were processed in accordance with U.S. Environmental Protection Agency (USEPA) procedures, with a holding time of 7 days and storage at 4 °C. The test for suspended solid concentration had a detection limit of 5.0 mg/L; samples less than this level were estimated at 2.5 mg/L.

In addition, monthly baseflow water samples were collected at these and five other locations (E1–E5, fig. 1) distributed across the watershed. In monthly sampling, streamflow velocity was measured using an Acoustic Doppler Velocimeter (FlowTracker, SonTek/YSI, Inc., San Diego, CA). The stream level and velocity data were used to develop a stage-discharge rating curve for the monitoring sites. A weather station (4-channel HOBO Micro Station, Onset Computer Corporation, Bourne, MA) was installed near stream sampling locations (WS, fig. 1) to obtain relevant climatic parameters of air temperature, precipitation, wind, and solar radiation.

Development of Stage-Discharge and Sediment Rating Curves

A stage-discharge rating curve was developed for each stream sample site using stream level and velocity measurements. The curve was fitted through a natural log transformation as given below:

$$\ln(Q(t)) = b_0 + b_1 \ln(L(t)) + \varepsilon(t)$$

where
Q = discharge (m^3/second)
$L(t)$ = stream level (m)

The stage gages and water level loggers installed at the extensive sites were used to similarly develop a discharge rating curve for each sample location. Relationships were initially determined between the extensive level stage-gage records and other intensive monitoring locations where daily level data was available for the study period. The water level loggers installed in January 2007 were used to relate discharges between all other extensive sites and an associated intensive site, where daily discharge information was available, to determine the extensive site daily discharges previous to the logger installation. Discharge at site E1 did not show a good relationship with any intensive site and subsequently could not be calculated. This may have been due to the spatial variation of precipitation inputs or differences in individual site characteristics.

A log-linear regression model was developed to estimate TSS and TDS loadings at all sites:

$$\ln(S_i(t)) = b_0 + b_1 \ln(Q_{day}(t)) + \varepsilon(t)$$

where
Q_{day} = daily discharge (m^3)
$S(t)$ = daily loading (kg)
i = the type of solid
$\varepsilon(t)$ = an error term assumed to be normally distributed.

The regression was performed using SAS Statistical Software (SAS Institute Inc., 1996). The fitted parameters used to estimate discharge and solids loadings are summarized in table 2. Stage-discharge relationships for I5 and I6, impacted heavily by beaver and debris dams, were unsuccessful and resulted in an inability to determine TSS and TDS loading relationships.

RESULTS AND DISCUSSION

Hydrologic Conditions

Precipitation during the study period from December 2005 to April 2007 was below the long-term average observed from 1971 to 2000 (National Climatic Data Center 2002). Only 3 months (Feb., Oct., and Dec. 2006) showed higher precipitation than the long-term average (fig. 2). Precipitation in March to September 2006 was low, representing 54 percent of the long-term average amount for the same period. The largest storm event occurred on Oct. 15 and 16 where 185 mm of rain fell, 11 percent of the entire 17 months observed.

Streamflow during the study period was similarly variable. Discharges generally peaked in February 2006 and December 2006/January 2007 due to a combination of high precipitation and wet antecedent conditions during those months (fig. 3). All sites experienced intermittent, no-flow conditions in the late summer months of 2006 due to low precipitation. The large storm in October 2006 came after this dry period and returned all streams to a connected, actively flowing status. Discharge is most likely underestimated for this month as streams extensively overflowed their banks, flooding the riparian zone and were beyond the extents of the developed stage-discharge relationships. Although bank overflow occurred several times during the course of the study, it was not as extreme or long lasting.

Seasonal and Spatial Variations in TSS and TDS Concentrations

TSS concentrations generally showed expected responses to streamflow conditions. Highest levels were observed following initial increases of streamflow after long dry periods, as in December 2005 and November 2006, and particularly in

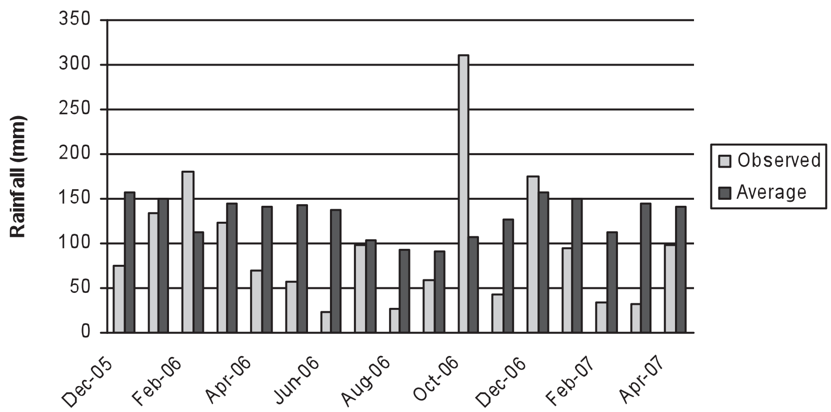

Figure 2—Monthly observed and average (1971–2001) precipitation for the 17-month study.

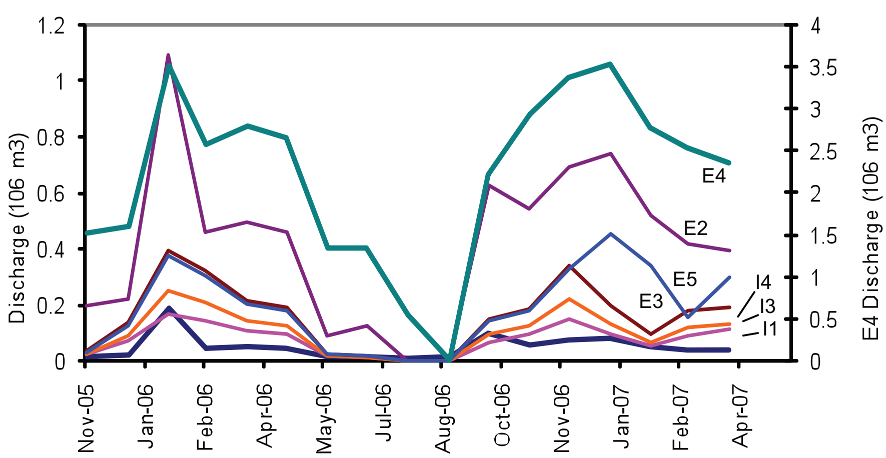

Figure 3—Total monthly discharge for all study sites where flow could be determined. E4 discharge is on the right ordinate due to a much higher magnitude of streamflow.

streams draining the largest areas (table 1). Generally, higher values were seen in the wet winter months, with lower values in the dry summer period. Average monthly values across all sites ranged from 5.7 mg/L in July 2006 to 38 mg/L in December 2005.

Mean monthly TDS concentrations from all sites ranged from 79.8 to 148.3 mg/L in December 2006 and December 2005, respectively (table 2). Generally, increasing values were observed as the streams returned from dry, no-flow conditions, to the higher winter discharges as in November and December 2006. This could possibly be due to higher levels of the local water table, increasing the influence of ground water on streamflow.

Although no clear spatial variation existed in suspended solid concentration, maximum values were highest in the streams with the largest drainage areas—E2 and E4 (fig. 4). Also, no clear spatial variation of TDS concentrations, due to position in the watershed or stream network, was found (fig. 4).

However, geomorphic characteristics may have played a role in concentration of TDS in a stream. Stream sites I1 and E2, that were straight and narrow with high velocities and had a high position upon the landscape, had the lowest overall TDS concentrations. Other sites with wider and deeper streams, and slower velocities, were at times characterized as pools due to extremely low flow, but contained a relatively large volume of water. Sites characterized as pools may provide greater time for the streamwater to interact with the adjacent soil and ground water in the hyporheic (adjacent riparian) zone, increasing TDS levels. Sharp TDS peaks in July 2006 during extremely low-flow conditions, and just before a majority of the streams became intermittent, suggest the same phenomena. Although site E4 also has higher velocity than most other sites, its wetted area was the largest and the

Table 1—Stream total suspended solid concentrations determined from monthly baseflow water sampling over the study period

	Total suspended solids						
Sites	I1	E3	I3	I4	E5	E2	E4
	mg/L						
Dec-05	12.0	19.0	9.0	15.0	37.0	70.0	105.0
Jan-06	2.5	2.5	12.1	16.1	12.1	14.1	10.1
Feb-06	8.1	25.5	16.2	11.2	19.1	11.1	21.2
Mar-06	9.2	14.3	9.2	5.1	9.2	5.1	2.5
Apr-06	25.5	22.9	23.5	28.3	25.5	20.1	20.0
May-06	8.1	9.1	5.2	2.5	10.2	19.2	2.5
Jun-06	14.4	14.2	13.3	20.5	2.5	—	19.3
Jul-06	6.2	2.5	2.5	9.1	5.1	5.0	9.3
Aug-06	6.1	34.1	—	9.0	2.5	—	2.5
Sep-06	—	—	—	—	6.1	—	—
Oct-06	19.2	—	—	—	—	—	—
Nov-06	25.9	19.0	26.9	26.1	28.3	43.6	39.8
Dec-06	2.5	25.9	23.1	24.3	25.5	19.4	26.7
Jan-07	8.1	14.1	14.1	13.1	23.3	6.2	19.6
Feb-07	17.4	17.2	10.1	10.2	15.2	7.1	6.1
Mar-07	25.2	28.6	31.6	18.3	28.2	18.3	30.6
Apr-07	15.2	17.0	19.6	15.1	19.3	22.2	34.4
Mean	12.8	17.7	15.5	14.9	16.8	20.1	23.3
±SD	±7.9	±8.9	±8.5	±7.5	±10.5	±18.2	±25.6

— = no flow during monthly sampling; SD = standard deviation.

Table 2—Stream total dissolved solid concentrations determined from monthly water baseflow sampling

	Total suspended solids						
Sites	I1	E3	I3	I4	E5	E2	E4
	mg/L						
Dec-05	74.0	186.0	145.0	169.0	121.0	90.0	253.0
Jan-06	91.1	113.5	140.9	135.9	109.9	93.9	140.9
Feb-06	92.9	77.5	102.8	108.8	123.9	83.9	79.8
Mar-06	87.4	100.7	126.8	141.9	130.8	96.9	106.5
Apr-06	82.5	111.1	115.5	108.7	116.5	100.9	109.0
May-06	126.9	124.9	148.8	105.5	141.8	117.8	99.5
Jun-06	72.8	118.8	114.7	116.5	126.5	—	154.7
Jul-06	70.5	64.2	118.5	104.9	92.4	56.7	116.7
Aug-06	106.9	130.9	—	117.0	162.5	—	173.5
Sep-06	—	—	—	—	128.9	—	—
Oct-06	107.8	—	—	—	—	—	—
Nov-06	86.1	101.0	117.1	108.9	79.7	71.4	59.6
Dec-06	98.5	61.6	82.9	101.7	62.7	65.2	86.3
Jan-07	108.9	99.9	96.9	64.3	99.7	94.8	96.4
Feb-07	89.6	114.8	123.9	97.8	132.8	99.9	124.9
Mar-07	120.8	100.4	123.4	145.7	139.8	86.7	101.4
Apr-07	156.8	104	133.4	138.9	150.7	100.8	120.6
Mean	98.3	107.3	120.8	117.7	120.0	89.2	121.5
±SD	±22.7	±29.7	±18.4	±25.1	±26.1	±16.6	±46.5

— = values represent no flow during monthly sampling; SD = standard deviation.

site was located in an area of extensive backwaters, providing a similar interaction with soils as the pooled sites.

Difference in TSS and TDS Concentrations between Baseflow and Storm Events

Stormflow can result in the highest rates of suspended solids loading due to increased erosion and the large volume of discharge water. Storm events in a forested catchment on Penang Hill, Malaysia, accounted for only 12.7 percent of the streamflow throughout the year, but were responsible for 60 percent of the TSS load (Ismail 2000). Storm sample TSS concentrations for this study ranged from <5.0 mg/L (I4, I5) to 109 mg/L (I1). Average storm samples of suspended solids consistently produced two to five times higher concentrations than average monthly baseflow samples for all sites (fig. 5). Sites I5 and I6, impacted most by beaver and debris dams, show the least differences between the two types of sampling. Increasing drainage area and stream size likely also contributed to the settling of sediments before reaching the most downstream sites, with dams simply increasing the magnitude of these effects.

Storm sample TDS concentrations across all sites ranged from 54.3 mg/L (I4) to 188.8 mg/L (I3). Mean concentrations generally increased with increasing drainage area and may be due to having a lower position in the watershed and more influenced by baseflow levels with higher TDS. Unlike the suspended sediments, TDS concentrations during the baseflow and storm events did not differ significantly except for at one site, I5 (fig. 5). Increased TDS concentrations in storm samples at I5 may have been influenced by runoff from a paved road and bridge located directly upstream of the site. No other site was located near a paved road.

Sediment Loading and Fluxes

Looking at the TSS loading over the study period (fig. 6), the level of streamflow shows a greater influence on loading than variations in concentration. Streamflow conditions, influenced

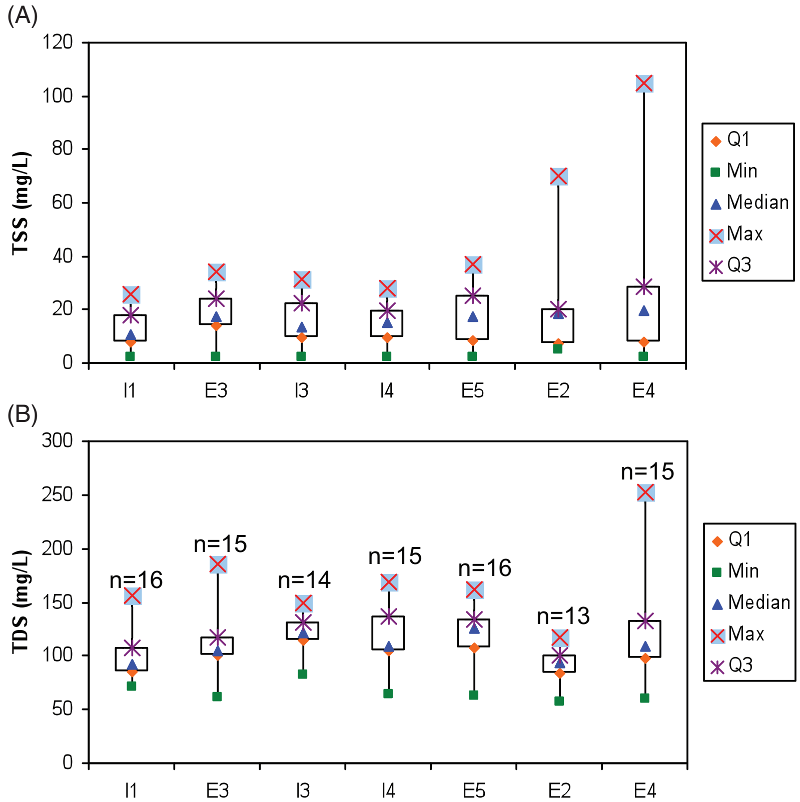

Figure 4—Box and whisker plots of monthly baseflow (A) total suspended solid and (B) total dissolved solid concentrations. Boxes show values in the middle 50 percent, bounded by first and third quartiles (Q1 and Q3) and sites are arranged from lowest to highest drainage area. Sample numbers (*n*) apply to both plots and variations are due to dry periods where no surface flow existed at the site and no sample was collected.

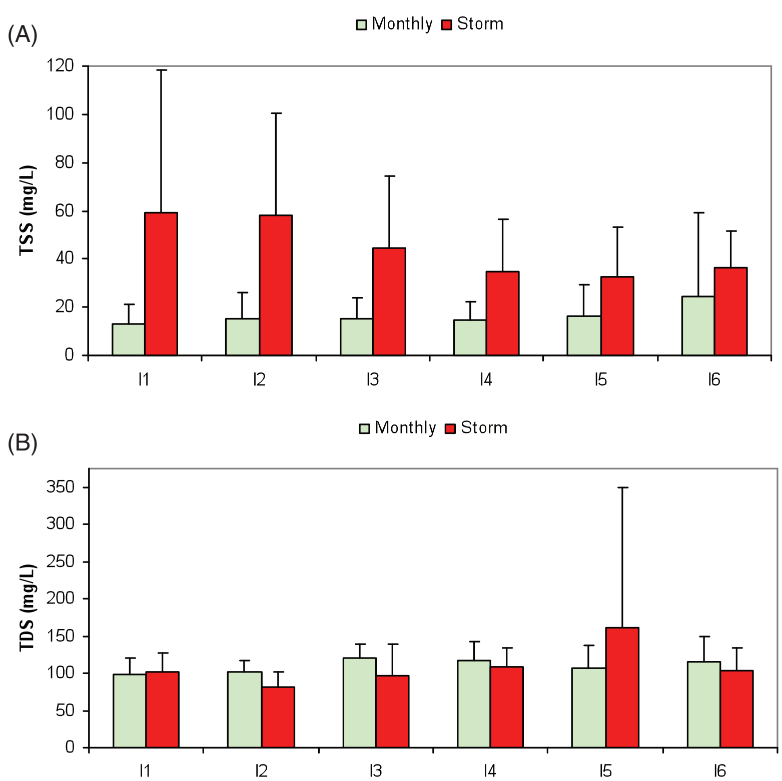

Figure 5—Average monthly baseflow and storm sample concentrations of (A) total suspended solid and (B) total dissolved solids with standard deviation bars.

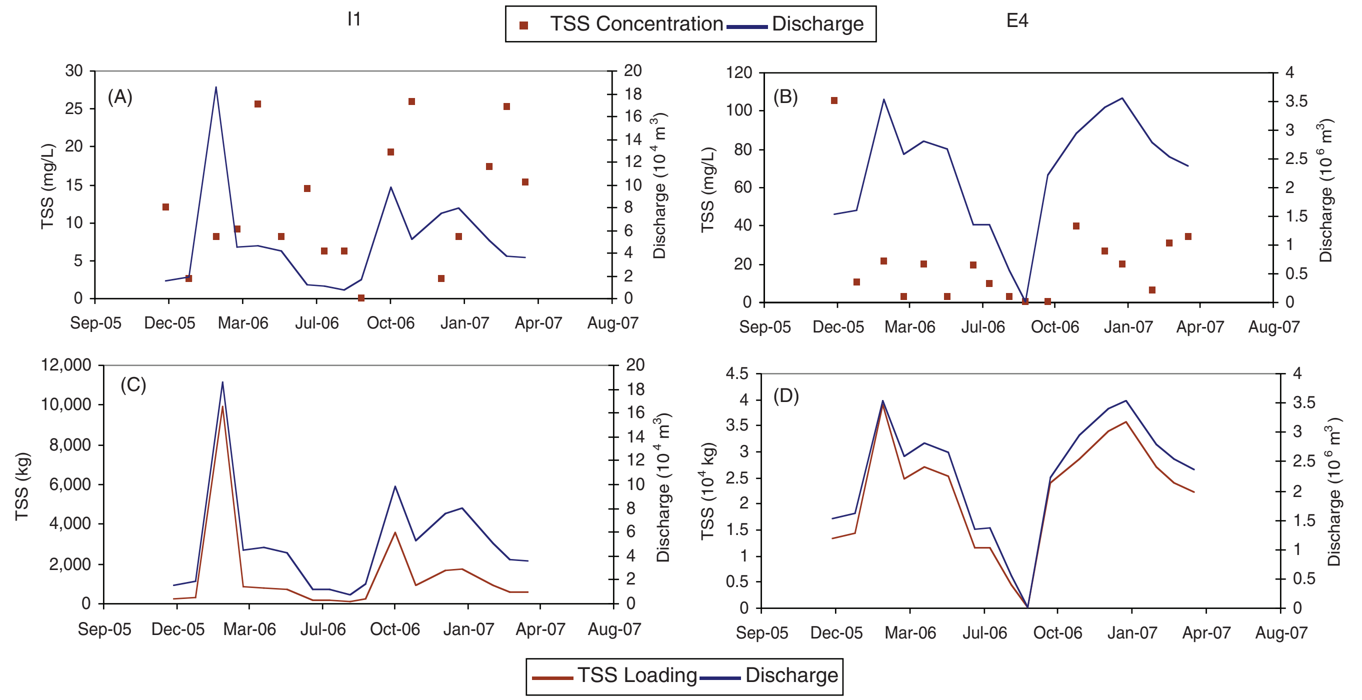

Figure 6—Comparisons of monthly discharge with monthly (A) and (B) total suspended solid (TSS) concentrations and (C) and (D) loadings for sites I1 and E4, the smallest and largest drainage areas, over the 17-month study period.

by characteristics such as antecedent moisture conditions and rainfall intensity/duration, would then have a lesser effect on TSS loading. Seasonal patterns of loading rates closely follow discharge, with high levels in the wet winter months and low levels in the drier summer. Site E5 appears to have higher rates of loading than all other sites except E4 in the winter.

As with suspended solids, monthly average TDS loads for all sites clearly followed the pattern of streamflow (fig. 7). Over the 17-month study period, total mass export of dissolved solids from the watershed was about 10 times higher than that of suspended solids. As the watershed is considered impaired by the USEPA for high TDS concentrations, further research on the complex hydrological processes present in the watershed, is needed to better determine the source of dissolved solids present in the stream.

Mean monthly TSS flux from the effective watershed outlet at site E4 was 0.8 kg/ha, increasing to 4.5 kg/ha at site I1. Site E2, the lowest monitoring location on Turkey Creek before draining into Flat Creek, had the lowest flux at 0.7 kg/ha/month. The higher discharge of Flat Creek at site E4 also carries a higher sediment flux than the input from Turkey Creek, even though it drains a larger area. Although these average fluxes cover two wet seasons and one dry season in the 17 months analyzed, precipitation was also 26 percent below normal for the study period, so fluxes may not be far from mean monthly value from 1 year with normal precipitation.

Patric and others (1984) compared sediment yields across the United States, and average annual yields for the eastern region were much greater than in Flat Creek, with 0.074 ton per acre (166 kg/ha) and 0.158 ton per acre (354 kg/ha) in watersheds less than and greater than 2 square miles (5.2 km^2), respectively. E2 (8.3 kg/ha/year) and E4 (9.0 kg/ha/year) were even lower than the lowest reported range of 0.01 ton per acre per year (22.4 kg/ha/year). Western regions in the study showed similar sediment yields, with only Pacific Coast forests showing significantly higher values (0.02 to 49.90 kg/ha/year). Due to the watershed hydrologic and geomorphic characteristics, forested land in the southeastern Coastal Plain appears to have among the lowest sediment yields in the United States.

CONCLUSIONS

Headwater streamflow in this low-gradient forested watershed was highly variable, from intermittent/no-flow conditions in the late summer, to high-volume overbank conditions in the winter season. Transitioning from the headwater streams to the watershed outlet, stream hydrologic response and streamflow variability decreased. Headwater response to storm events was quick, while hydrographs of increasing drainage area had longer lag times and more gradual falling limb recessions. The flat slopes, low-permeable soils, and beaver/debris dams reduced peak discharges, later releasing the stored water to extend streamflow during dry periods. These effects were compounded, and are most prevalently shown, at the watershed outlet. These physical watershed characteristics impacting the stream hydrology are the major influence on sediment loading in Flat Creek.

Suspended and dissolved solid concentrations during baseflow showed little seasonal variation. Mass loadings were

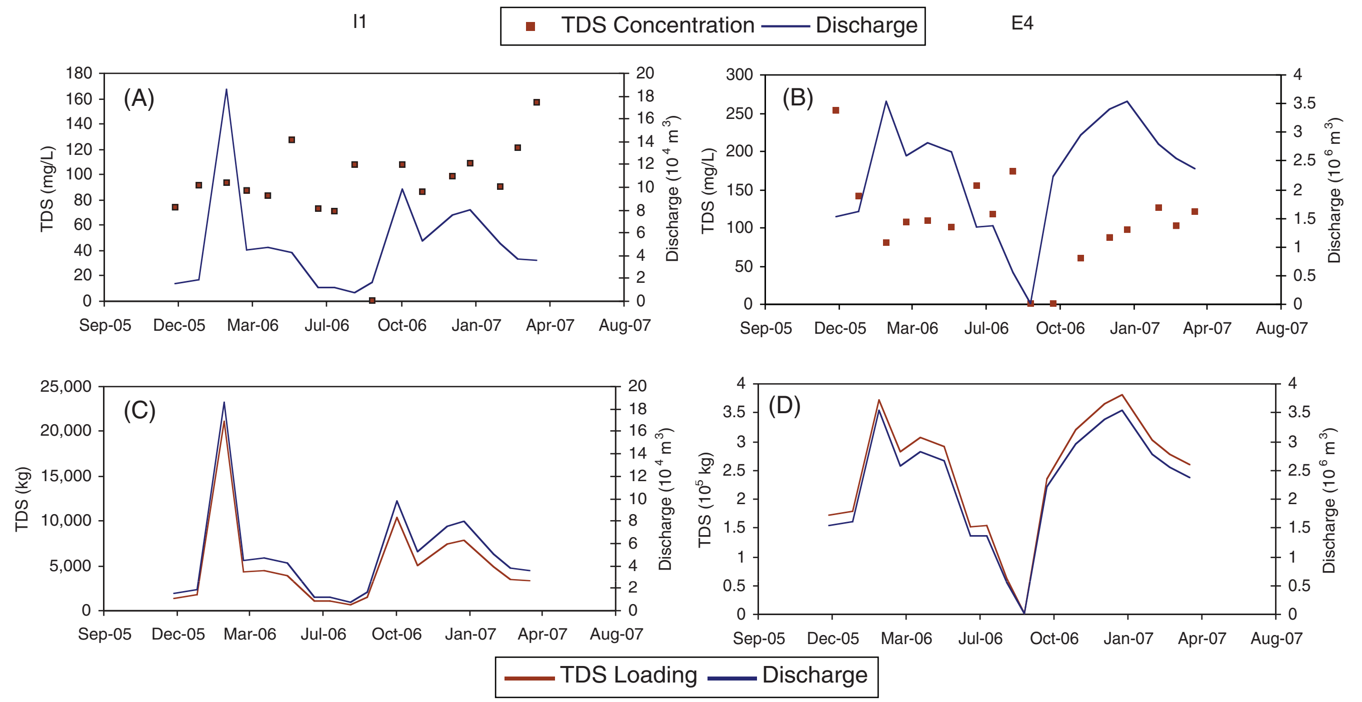

Figure 7—Comparisons of monthly discharge with monthly (A) and (B) total dissolved solid (TDS) concentrations and (C) and (D) loadings for sites I1 and E4, the smallest and largest drainage areas, over the 17-month study period.

influenced more by the discharge regime than fluctuations in concentration. Sediment yield from the watershed was low, indicating that sediment transport in low-gradient headwaters is highly retentive. As most of the land use in Flat Creek is commercial pine plantation, the attenuated runoff decreases erosion susceptibility from harvesting activities. However, caution must also be taken and forestry best management practices implemented as harvest sites can become quickly saturated following precipitation events, creating the potential for direct surface runoff and sediment delivery to streams.

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