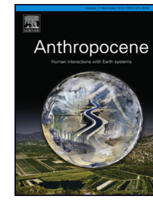
Anthropocene 25 (2019) 100188

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene



Hydrologic, geomorphic, and stratigraphic controls on suspended sediment transport dynamics, Big Harris Creek restoration site, North Carolina, USA

Jerry R. Miller*, Kelly Ferri, David Grow, Lionel Villarroel

Department of Geosciences and Natural Resources, Western Carolina University, Cullowhee, NC, 28723, USA

A R T I C L E I N F O

Article history:
Received 10 May 2018
Received in revised form 6 December 2018
Accepted 23 December 2018
Available online 3 January 2019

Keywords:
Suspended sediment transport
River restoration
Legacy sediments
Geomorphic response

A B S T R A C T

Water quality monitoring records were combined with geomorphic and stratigraphic data to determine the controls on suspended sediment transport dynamics within the headwaters of Big Harris Creek, the site of one of the largest stream restoration projects in North Carolina, USA. Land-use change associated with European settlement resulted in spatially variable geomorphic responses that produced reaches possessing semi-homogeneous landforms and processes, referred to as process zones. Downstream, process zones were dominated by entrenched channels possessing banks characterized by sandy post-settlement deposits that overlie finer-grained pre-settlement deposits. Spatial variations in the resulting process zones strongly influenced modern suspended sediment concentrations (SSC) and loads in the catchment, which are among the highest reported for the southeastern United States. The source and transport dynamics of suspended sediment differed between low magnitude floods (characterized by minimal changes in water level elevations) and moderate to high magnitude floods. Low magnitude floods were characterized by SSCs that varied over several orders of magnitude, and that were unrelated to flow conditions. Precipitation, during these events, rapidly mobilization fine-grained pre-settlement deposits associated with bank failures and cattle crossings along entrenched alluvial channels. Moderate to high magnitude floods within larger tributary basins exhibited more systematic discharge-SSC relationships. Suspended sediment transport was dominated by sand-sized particles derived from post-settlement legacy sediments eroded from the channel banks and headwater gullies. The observed temporal and spatial differences in SSC between low and moderate to high magnitude floods complicates the quantification of water quality, and shows that comparisons of water quality before and following the implementation of restoration projects need to differentiate between distinct populations of suspended sediment transport.

1. Introduction

During the past decade, a plethora of definitions have been put forth for the practice of ‘stream restoration’, hindering its use as a specific descriptor of the management strategies that are applied. Nonetheless, inherent in most definitions is an attempt to improve aquatic and/or riparian ecosystem function and health from an ecological perspective (see, for example, Hobbs and Norton, 1996). Expenditures on restoration projects in the U.S. now exceed approximately one billion dollars per year (Bernhardt et al., 2005). These projects are most frequently intended to improve water quality, reduce bank erosion and channel instability, enhance selected biotic species, and hydrologically reconnect the channel to its floodplain (i.e., the riparian zone). With regards to water quality, a common goal is to reduce suspended sediment loads (Miller and Kochel, 2008, 2013), which often threaten aquatic ecosystems (Wood and Armitage, 1997; Armstrong et al., 2003; Syvitski et al., 2005; Kemp et al., 2011; Grabowski et al., 2014). In fact, according to the National Water Quality Inventory, a program developed to assess the current condition of the nation’s water resources, sediment is second only to pathogens (e.g., *E. coli*) as the leading

Abbreviations: BH1, montoring station at mouth of basin on Big Harris Creek; BH2, upstream monitoring station on Big Harris Creek; BHT1, monitoring station at mouth of Royster Creek; BHT2, monitoring station near confluence of Fletcher and Stick Elliott creeks; cms, cubic meters per second; DOC, dissolved organic carbon; Hrlt, hourly rainfall intensity; NC, North Carolina; NRCS, United States National Resource Conservation Service; SSC, suspended sediment concentration; SSC_{max}, maximum event suspended sediment concentration; Tprec, total precipitation of an event; USGS, United States Geological Survey.

* Corresponding author at: Department of Geosciences and Natural Resources, Western Carolina University, Stillwell 302, Cullowhee, NC, 28723, USA.
E-mail address: jmiller@wcu.edu (J.R. Miller).

https://doi.org/10.1016/j.ancene.2018.12.002
2213-3054/

cause of river impairment (USEPA, 2013). Moreover, the annual cost of suspended sediment influx to riverine ecosystems is estimated to range from $20 to $50 billion in North America alone (Pimentel et al., 1995; Mukundan et al., 2012; Bain et al., 2012).

The effectiveness of river restoration to address the “sediment problem” is strongly correlated to the degree with which the sources, transport and redeposition of suspended materials are understood within the basin (Vercruysse et al., 2017). Unfortunately, such information is lacking for an overwhelming majority of sites and regions where restoration is conducted. Data pertaining to small headwater basins are particularly lacking, even though they account for more than 70% of total stream length in the continental United States (Leopold et al., 1964).

The primary objective of this investigation was to combine an extensive set of monitoring data with geomorphic and stratigraphic data to document the sources of suspended sediment, and the controls on suspended sediment transport, within the headwaters of Big Harris Creek over a range of temporal and spatial scales. Specific research questions include: (1) What were the variations in suspended sediment concentration during and between flood events? (2) How did suspended sediment concentrations and loads vary spatially within the basin? (3) What were the responses of the system to anthropogenic land-use changes that affected the basin near the turn of 20th century? (4) How did spatial differences in channel response, and the produced alluvial stratigraphic units, influence the contemporary influx of sediment to and through the river? The combined analysis provides insights into the assessment of water quality improvements associated with restoration projects, and the controls on suspended sediment transport dynamics that are not only applicable to Big Harris Creek, but other headwater streams.

2. Methods

2.1. Study area

The study area includes the upper 9.6 km^2 of the Big Harris Creek watershed located within the piedmont physiographic province, approximately 2 km from the town of Polkville, North Carolina, USA (Fig. 1). The site represents one of the largest and most expensive stream restoration projects in North Carolina. Land-use/land-cover within the project area is currently dominated by forest (˜48%) and grassed/pastured areas (˜44%). The remainder of the land-use/land-cover types include turkey farming facilities, homes, roads, and row crops (Fig. 1). Both the axial channel of Big Harris Creek and its major tributaries were incised (prior to restoration) into alluvial valley floor deposits. Incision varied along the drainage network, and ranged from approximately 1.5 to more than 4 m. Prior to restoration, cattle were grazed in many of the areas covered in pasture, and locally crossed stream channels where they trampled bank vegetation and bank materials. River restoration was initiated, in part, to reduce the rates of bank erosion, improve water quality, and hydrologically reconnect selected channel reaches with its floodplain.

2.2. Description of monitoring sites

Four sites within the Big Harris Creek project area were selected and instrumented between August and November 2012, and monitored through April 2017 (Table 1). These four sites were selected to characterize the total sediment load and yield from the basin (BH1, Fig. 1), as well as spatial differences in sediment concentrations, loads, and yields between subbasins in the project area (BH2, BHT1, BHT2). Each site was instrumented with a HOBO levellogger to record fluctuations in water levels (and discharge), and an ISCO automated water sampler. In addition, passive (U59B) siphon samplers were installed and maintained by the NC Division of Water Quality from December 2012 through December 2013 at all four sites possessing ISCOs, and at an additional 11 sites to increase the spatial resolution of the SSC data (Fig. 1). At most sites, three to four passive samplers were located at different heights above the channel bed to collect water samples under varying flow conditions. The passive samples did not record the timing of sample collection, and only obtain waters during the rise stage of a flood. Nonetheless, they provided a low-cost method of increasing the spatial resolution of the SSC data (MacKay and Taylor, 2012).

Upon collection, water levels were converted into discharge by (1) modeling the stage-discharge relationship at the site, (2) fitting a statistical model to the generated stage-discharge data, and (3) using the statistical regression model to convert water levels to discharge. Stage-discharge relationships were modeled using a Cross Section Hydraulic Analyzer developed by the NRCS (Moore, 2009), and verified by comparing estimated discharge values to discharge measurements collected during storm events.

Water samples were collected in pre-cleaned 1000 ml bottles by the ISCO automated samplers. The ISCOs were programmed to start sampling at the beginning of a flood event (as determined by a change in water level). Samples were then obtained at 30 min intervals, regardless of flood magnitude. On occasion, samplers failed during the sampling of a flood event. As a result, samples were not always obtained during the entire event, or were collected at intervals other than every 30-minutes. All ISCO and U59B samples were analyzed for SSC using a slightly modified version of the procedure developed by the USGS (Guy, 1977). The detection limit was determined to be 2.5 mg/L; precision and accuracy of the method, determined using an in-house standard, were within +/- 5% of known SSC values.

Following the preliminary analysis of the sediment data in 2015, it was decided that SSC concentrations were adequately characterized for low magnitude floods. Thus, samples collected during low magnitude events were not analyzed for SSC after 2015; only samples obtained during moderate to high magnitude floods were analyzed. Site BH2 was an exception in that a total of 135 samples were collected to characterize changes in SSC following the influx of sediment to the channel from an upstream area of clearcut logging that occurred in 2016.

2.3. Collection and analysis of precipitation data

Precipitation data were collected using a tipping bucket rain gauge located near the center of the basin (Fig. 1) between February 27, 2012 and August 5, 2014. Failure of the rain gauge prohibited the collection of data from more recent events. Precipitation events for which SSC data were also available were characterized in terms of their total rainfall, duration, average intensity, and maximum 1-hr intensity.

2.4. Calculation of sediment loads and basin sediment yields

A wide range of approaches have been put forth to calculate sediment loads, all of which possess advantages and disadvantages (see Letcher et al., 1999; Richards, 2001; Degens and Donohue, 2002, for reviews). When the sampling program was established we had intended to use extrapolation methods to calculate load because it was expected that SSC data would not be available for rare, high magnitude floods. However, the lack of strong, statistically significant relationships between discharge and SSC over the sampling period led to the use of a flow-weighted, averaging method patterned after Walling and

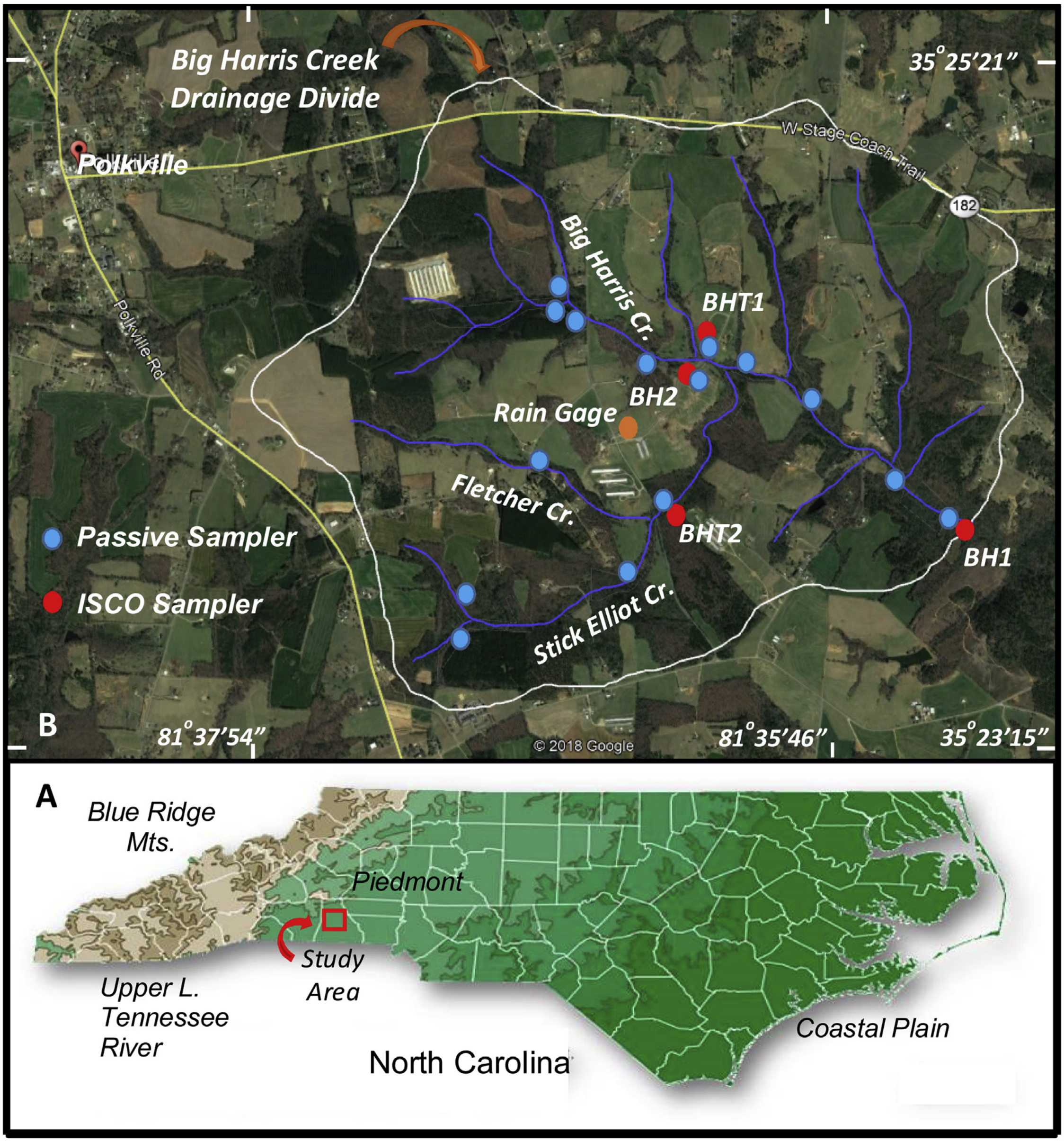


Fig. 1. Location of the Big Harris Creek basin in North Carolina (A), and location of the rain gauge, the four water quality monitoring stations, and the passive samplers within the project area (B). Image shows land-cover in March 19, 2017. Spot Image obtained from Google Earth, April 2018.

Webb (1981). Mathematically, it is expressed as:

$$Load = K\sum(qr\sum_{i=1}^{i}(\frac{Cri}{n})) \qquad (1)$$

where K is a conversion factor to account for units and the period of reporting, C*ri* is the median concentration of the individual samples within a specified interval of flow duration *(r)*, q_r is the centroid discharge of the specified interval of flow, and *n* is the number of samples within the specified interval of flow. The median, rather than the mean, SSC value was used because outliers significantly altered mean SSC values at the sites. As is common, the flow interval used in the analysis varied such that it was minimized at high flow and increased for low flows.

2.5. Mapping of process zones

Recent studies have shown that the magnitude, rate, and dominant type(s) of geomorphic process(es) operating within and adjacent to a river channel may not systematically vary along the drainage network, but change abruptly downstream between stream segments (Montgomery and Buffington, 1993, 1997; Grant and Swanson, 1995; Miller et al., 2012). In order to capture abrupt spatial variations in channel and valley form, processes, and behavior, many investigators have applied a hierarchical analysis of drainage networks (Montgomery and Buffington, 1993; Grant and Swanson, 1995; Fryirs and Brierley, 2001; Miller et al., 2012, 2013). Reach-scale units, referred to as process domains (Montgomery and Buffington, 1993, 1997) or process zones (Brierley and Fryirs, 2005) are particularly well-suited for management purposes as they include segments of the stream channel and adjacent valley floor that are characterized by homogenous landforms and processes. In this study, process zones were defined, characterized, and mapped on the basis of channel slope, depth of channel incision, degree of bank erosion, presence of bedrock exposures, occurrence of knickpoints and headcuts, width and sediment storage potential of the valley and floodplain, and the existence of wetlands.

Table 1
Location and general characteristics of suspended sediment sampling sites. See Fig. 1 for site locations.

Site Number	Basin Area (km^2)	Instrumentation	Monitoring Period	Additional Comments
BH1	9.61	• ISCO • Levellogger • Turbidity Probe • U59B samplers	11/1/2012 to 04/30/2017	Channel is incised ~3 m below the valley floor, and is characterized by easily eroded, vertical or near vertical banks, and a mobile channel bed
BH2	2.12	• ISCO • Levellogger • U59B samplers	8/22/2012 to 04/30/2017	Reach characterized by relatively high gradient, large channel bed material and local exposures of bedrock
BHT1	0.64	• ISCO • Levellogger • U59B samplers	8/21/2012 to 04/30/2017	Site is close to BH2; channel characteristics differ; slope at BHT2 is lower and bed material is significantly smaller
BHT2	3.29	• ISCO • Levellogger • U59B samplers	8/21/2012 to 04/30/2017	Site 11 is located on a tributary to Big Harris Creek; channel is incised several meters below the valley floor; channel bed dominated by sand-sized sediments. Reach characterized by periodic passage of sand sheets

2.6. Stratigraphic and dendrochronologic analyses

The alluvial (and colluvial) stratigraphy exposed in the channel banks was described at 21 locations within the basin (Fig. 2). Deposits along some reaches could not be described because of an inability to gain property access from landowners. Delineation of stratigraphic units and facies followed the procedures outlined in Kottlowski (1965) and Bridge (2006). Contemporary and historic deposits were separated on the basis of historic artifacts buried in the deposits, and the degree of sediment weathering (soils). Correlations were performed, where possible, on the basis of topographic and stratigraphic position, unit sedimentology, weathering characteristics, cross-cutting relationships, and dendrochronological dating methods. Absolute deposit age was also documented using radiocarbon dating methods. Radiocarbon analyses were performed by International Chemical Inc., located in Sunrise, Florida, USA.

The drainage network within the headwaters of Big Harris Creek was lined by a nearly continuous cover of trees (Fig. 1), primarily consisting of tulip poplars (genus – *Liriodendron*). The channel banks could not be defined through the tree cover, inhibiting the use of sequential aerial photographs to document bank erosion rates. However, most trees, particularly along process zones dominated by wide alluvial valleys, exhibited an extensive network of roots that had been exposed by corrasion and slab failures. Decadal-scale rates of bank erosion were estimated using dendrogeomorphic methods (patterned after Hupp and Bornette, 2016) by determining the amount of erosion that had occurred around the roots of dendrochronologically dated trees growing along the upper edge of the channel bank. More specifically, bank erosion was estimated as the distance from the bank to the most distant root exposed within the channel (i.e., the amount of erosion), divided by the determined age of the tree. Given that time since tree germination was used in the calculation, the method provides a conservative (minimum) estimate of erosion at the site.

Additional trees were also sampled (cored) to determine the approximate time of valley floor stabilization as indicated by tree germination. In total, 35 trees were sampled using a Swedish increment borer. At least two cores were taken from each tree at approximately 1 m above the ground. Samples were mounted and prepared according to procedures described by Stokes and Smiley (1996). Samples were sanded with up to 400 grit sandpaper, examined under a microscope, and cross-dated using skeleton plots.

2.7. Statistical analyses

Time series and other plot types were created using Origin 9.1. All other statistical analyses were conducted using SYSTAT 9.0.

3. Results

3.1. Monitored hydrologic events

Water level fluctuations were recorded at four monitoring sites (BH1, BH1, BHT1, BHT2) at 5-minute intervals (Table 2). Significant differences exist in the number, timing, and magnitude of flood events recorded at the monitoring stations (data not shown). While some events were observed at all sites, others were only observed at a few. Noted variations presumably reflect spatial differences in rainfall and upstream basin characteristics (e.g., basin area, relief, land-use, soil type, etc.)(Table 3). The range of monitored flows was impacted by a significant drought in 2015 and 2016. The USGS National Streamflow Statistics (NSS) package (Ries, 2006) was used to estimate the recurrence interval of the largest recorded flood. The largest flood at BH1, the downstream most monitoring station, was estimated to be a 25- to 30-year event, whereas the largest monitored flood at BHT2 was estimated to be about a 5-year flood (Table 2). NSS is not recommended for application to small basins; thus, accurate estimates could not be generated for BH2 and BHT1. The generated estimates suggest that SSC data were obtained over a moderate range of discharge conditions.

3.2. Suspended sediment concentrations and loads

3.2.1. Magnitude and spatial differences in SSC and loads

Mean SSC values at the four sites ranged from 632 mg/L at BH1 to 1109 mg/L at BH2, the latter following the localized clearcutting of trees in the subbasin's headwaters (Table 4). Median values tended to be lower, particularly for BH2, as the mean was strongly influenced by a few high SSC measurements (Table 4). Maximum values exceeded 7165 mg/L at the four sites, and was greater than 9830 mg/L at the three upstream monitoring sites.

SSC values documented using passive (U59B) samplers were often higher than those measured using ISCO automated samplers (Table 4), including at sites where sampler types were co-located. The ISCO samplers collected water and sediment from a single height above the channel bed, but at multiple (up to 24) times during the entire flood. In contrast, passive samplers collected water immediately below the water surface during rising flow conditions, but at 3 to 4 heights above the channel bed. As shown

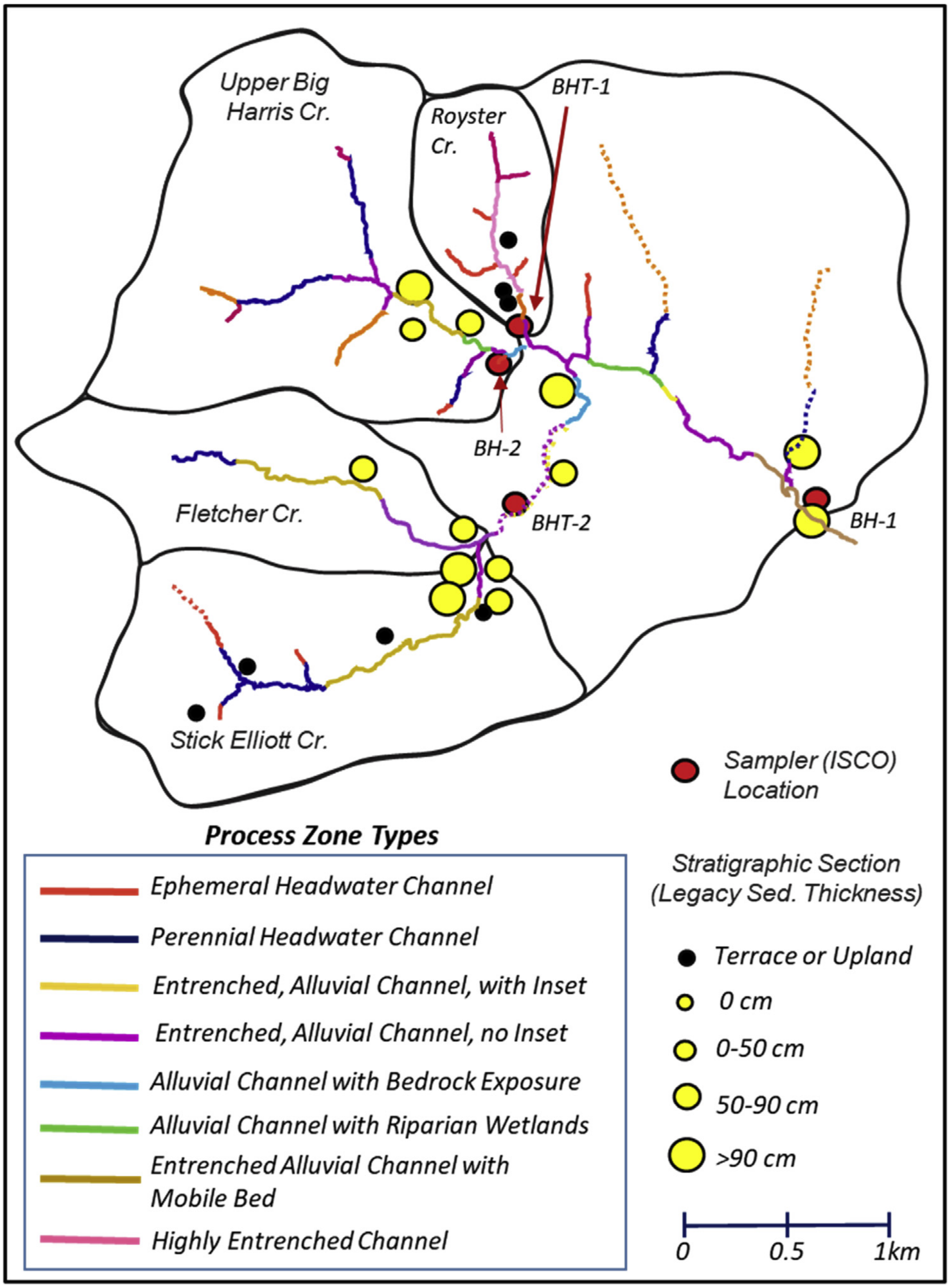


Fig. 2. Map of the Big Harris Basin. Drainage divides of subbasins are delineated by solid black lines. Colored lines show the distribution of process zone types within the basin. Dashed lines indicate type of process zone has not been field verified. See Table 6 for process zone characteristics.

Table 2
Descriptive statistics of discharge measured at the four monitoring sites.

Site	n[a]	Mean[b] (cms)	Maximum (cms)	RI Max[c] (years)
BH1	368,716	0.1258	29.478	25-30
BH2	377,406	0.020	0.825	–[d]
BHT1	407,927	0.0835	1.487	–[d]
BHT2	282,538	0.1352	9.199	5

[a] Number of measurements made at 5-minute intervals at the site.
[b] Based on mean of all measurements taken.
[c] Estimated recurrence interval of maximum event recorded during monitoring period; determined using rural parametric equation for North Carolina as contained in the USGS National Streamflow Statistics program (NSS).
[d] Application of NSS to basins less than 2.59 km^2 (1 mi^2) is not recommended; thus, values not provided.

Table 3
Summary of selected basin morphometric and land-use characteristics within the basins upstream of the monitoring sites. Land-use mapping based on March 19, 2017 Google Earth Imagery.

	BH1 (Total Basin)	BHT2	BH2	BHT1
Basin Area (km^2)	9.61	3.29	2.12	0.64
Basin Relief (m)	67.06	42.67	48.77	36.58
Basin Length (km)	3.61	2.01	1.92	1.21
Land-Use (% of total area)				
Forest	47.6	56.7	61.6	6.6
Pasture, Lawns, etc.	43.5	32.3	28.7	61.0
Row Crops & Barren Ground	7.3	9.5	8.1	29.7
Impervious Cover	1.5	1.5	1.6	2.7
Basin Area (km^2)	9.61	3.29	2.12	0.64

Table 4
Statistical summary of collected SSC data; concentrations presented in mg/L.

Site	*n*	Mean	Minimum	Median	Maximum
BH1	406	632	2.5	385	7165
BH2 (total)	287	1109	2.5	221	10,342
BHT1	139	713	24	216	9,832
BHT2	154	803	43	415	11,081
Passive	153	2,322	80	1,446	13,961
BH2 (total)	287	1109	2.5	221	10,342
BH2 (Pre-Cutting)	152	182	8.8	92	9,586
BH2 (post-Cutting)	135	1,477	2.5	848	10,342

below, concentrations of suspended sediments were often higher during the onset of a flood than during the falling stage of the flood. Thus, differences in measured SSC between samplers reflect, in part, differences in the timing and position of sample collection with the water column. Other factors, such as the active versus passive collection of river water, may also have contributed to the observed differences in SSC values.

Spatially, SSC measured by the passive samplers varied in a manner that is consistent with the data collected at the ISCO automated sites (Fig. 3). SSC was relatively low in BH2 and along the lower reaches of Big Harris Creek (immediately upstream of BH1) in comparison to BHT1 and BHT2 (prior to clearcutting in the BH2 subbasin).

Sediment loads for the four monitoring sites were calculated using Eq. (1). Catchment wide, sediment loads varied from 529 tonnes/yr at BH2 to 3895 tonnes/yr at BH1 (Table 5). In contrast to total suspended sediment loads, the highest sediment yields, 1649 tonnes/km^2/yr were measured in BHT1 (the smallest monitored subbasin) (Table 5).

3.2.2. Temporal variations in SSC over the monitoring period

During low magnitude flood events, large increases in SSC occurred at all four sites before significant increases in discharge.

Table 5
Summary of suspended sediment loads and basin sediment yields.

Statistic	BH1	BH2	BHT1	BHT2
Load (tonnes/year)	3895	529	1,056	2,256
Sediment yield (tonnes/km2/year)	425	249	1649	687

SSC values used in calculation based on median value for specific range of discharge exceedance.

Thus, discharge-SSC relationships were either poorly-defined, or exhibited nearly vertical trends, indicating that SSC is semi-independent of discharge (Fig. 4). In contrast, during moderate to high magnitude floods a statistically significant trend exists ($p < 0.05$) between discharge and SSC at BH1, although the trend is characterized by considerable variability (Fig. 4a). At a discharge of 1 cubic meter per second (cms), for example, SSC varied from a few hundred to a few thousand mg/L. Discharge-SSC relationships were more strongly defined for individual floods, as is evident on Fig. 4a as linear data point ‘trails’ shown by the blue circles.

Data from BH2 was also characterized by two distinct populations of flood events (Fig. 4d), although the statistically significant relationship between discharge and SSC is less pronounced. At the two upstream most sites (BH2, BHT1), statistically significant relationships between discharge and SSC existed during some individual moderate to high magnitude floods. However, when data from multiple events was combined, no relationship was present (Fig. 4b, c).

On March 2, 2016, a large amount of fine-grained (< 63 μm) sediment was observed on the bed of the channel at and upstream of BH2. The sediment was derived from the clearcutting of trees from a 0.20 km^2 area in the headwaters of the subbasin. The influx of sediment was accompanied by a temporary increase in SSC at BH2 (Table 4). A *t*-test demonstrated that there was a statistically significant ($p < 0.05$) difference in SSC between pre- and post-cutting periods. The increase in SSC did not influence concentrations further downstream at BH1.

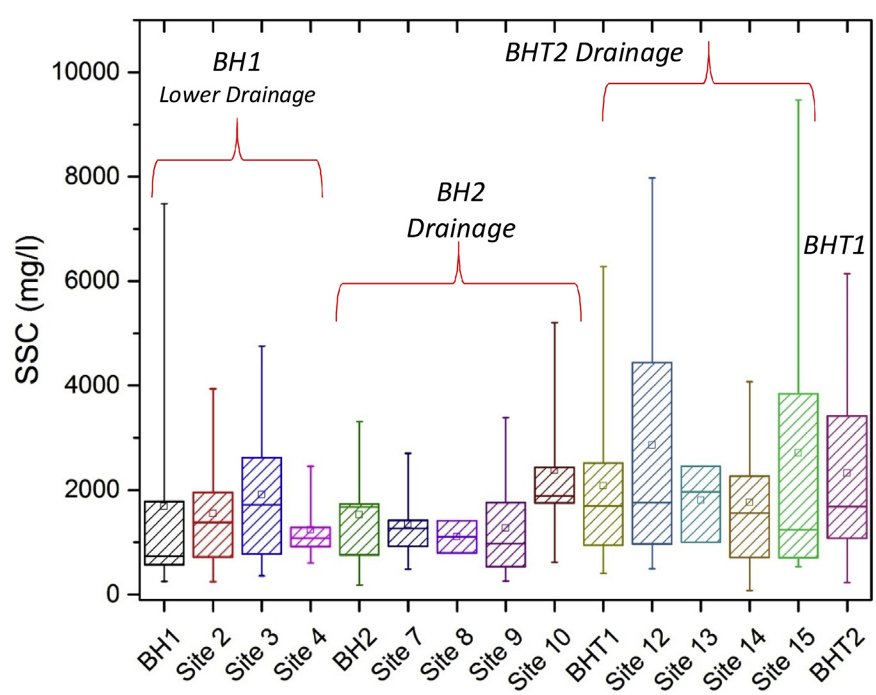


Fig. 3. SSC data collected using U59B passive samples located at 15 sites in the basin. With one exception in each area, mean SSC is lower along the channel drained by BH2 and the lower reach of Big Harris Creek (labeled BH1). See Fig. 1 for sampler locations.

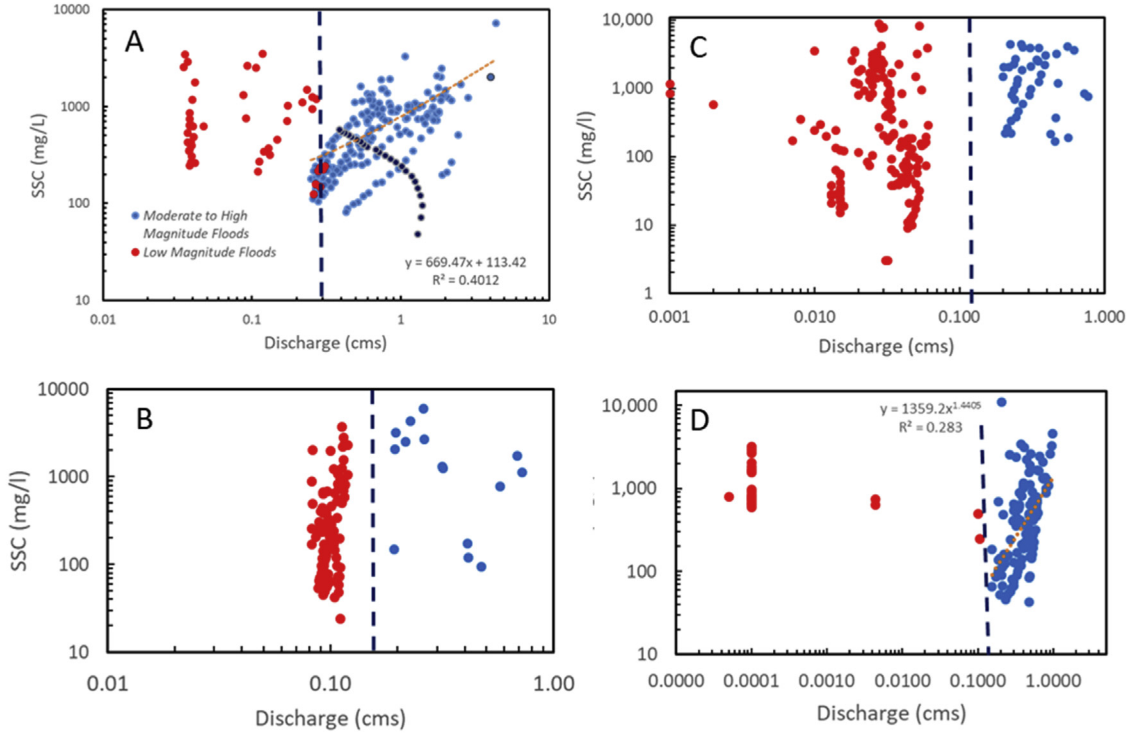


Fig. 4. Relations between discharge and suspended sediment concentration (SSC) at (A) BH1, (B) BHT1, (C) BH2, and (D) BHT2. Note large variations (exceeding 1–2 orders of magnitude) in SSC over a narrow range of discharge during low flow conditions. Dashed vertical line defines discharge threshold between low and moderate/high magnitude floods. Red circles – data from low magnitude floods; Blue circles – data from moderate to high magnitude floods. Statistically significant relationships between SSC and discharge (dashed orange line) occurred during moderate and larger events within the larger basins represented by BH1 (A) and BHT2 (D). Inverse relationship observed in plot A (dark blue circles) is primarily associated the April 27, 2013 flood (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

3.2.3. Variations in SSC during individual flood events

As noted above, semi-systematic direct relationships between discharge and SSC were common during moderate to high magnitude floods. Nonetheless, variations in SSC were far from simple. The most systematic variations in SSC and discharge occurred at BH1 during moderate to large floods (Fig. 5). In the simplest case, SSC peaked before peak discharge (Fig. 5a) creating a phenomenon known as hysteresis in which SSC for a given discharge exhibited two (or more) distinct values during a single event depending on whether the sample was collected during the rising or falling phase of the flood. The most commonly observed form of hysteresis was a clockwise loop, such as that which occurred on July 4, 2013 at site BH1 (Fig. 5b). In this case, SSC is higher during the rising limb of the hydrograph than the falling limb. At a discharge of 0.6 cms, for example, SSC was more than 3 times higher (˜1300 mg/L) during the rising limb than for the same discharge during the falling limb of the hydrograph (when it as about 400 mg/L)(Fig. 5b).

Clockwise-hysteresis was also observed at the other three monitoring sites. However, hysteresis was often more complicated at these sites, particularly when the flood was associated with multiple periods of relatively intense precipitation. More importantly, the peak in SSC often occurred very early in the flood; in some instances, SSC rose rapidly with the onset of precipitation and peaked before significant increases in flow (Fig. 5c). Turbidity data collected at BH1 exhibited similar trends (see Fig. S1 in Supplementary Materials).

Counter-clockwise hysteresis was occasionally observed at BH2, BHT1, and BHT2; it was particularly common at BH2 (Fig. 5f). During some discharge events that exhibited multiple periods of high flow, SSC rose during the initial phase of the flood (creating clockwise hysteresis). SSC then rose again following subsequent peaks in discharge, creating a counter-clockwise hysteretic loop (Fig. 5e,f).

3.3. Analysis of storm related controls on SSC

To gain additional insights into the controls on SSC, precipitation data collected near the center of the basin (Fig. 1) was related to maximum event SSC. A total of 27 storms for which both precipitation and SSC data were collected were available between February 27, 2012 and August 5, 2014. Relationships between SSC and total rainfall, duration, average intensity, and maximum intensity were determined for each of the four monitoring sites using stepwise multiple regression. The analysis revealed that variations in SSC at BH1 can be explained, in part, by total event precipitation (T_{prec}) and average hourly rainfall intensity (HrIt), such that:

$$SSC_{max} = -61.41 + 2705.1 HrIt + 491.4 T_{prec} \quad (2)$$

The relationship is statistically significant ($p < 0.05$), and explained 47% of the total variability in SSC values.

Stepwise regression conducted on data from BH2 produced a model in which total event rainfall explained about 33% of the variation in maximum flood SSC. Statistically significant regression equations could not be developed for BHT1 or BHT2, in part because data for all parameters were available for only 11 and 12 events, respectively.

3.4. Type and distribution of process zones

Process zones represent channel/valley reaches characterized by semi-homogeneous landforms and geomorphic processes. Eight different types of process zones were defined within the Big Harris

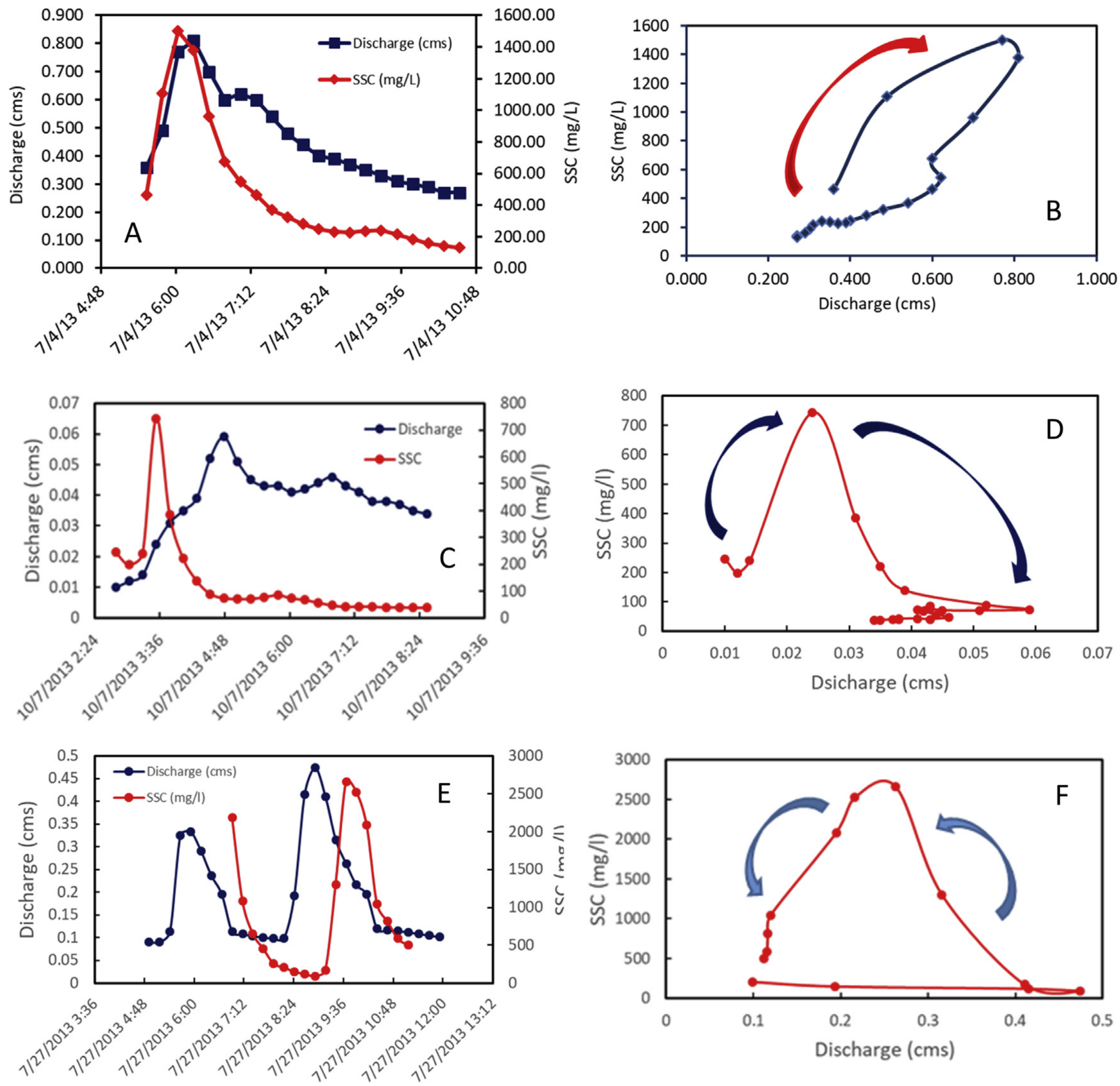


Fig. 5. Variations in discharge and SSC at BH1 during flood events on July 4, 2013 (A) and the associated hysteresis loops (B). (C) Variations in discharge and SSC at BH2 during an event on October 7, 2013, and the hysteresis loop observed during the event (D). Note that the initial increase in suspended sediment concentrations occurred at the start of rising water levels and create a clock-wise hysteretic loop. In contrast, variations in discharge and SSC during an event on July 27, 2013 flood at BHT1 (E) created a counter-clockwise hysteresis loop at BHT1 if data collected during the second rise in discharge are considered (F).

Creek project area (Fig. 6). The spatial distribution of the process zones is shown in Fig. 2 and quantified in Figure S1; their characteristics are provided in Table 6. A more detailed description of the similarities and differences of the defined process zones is provided with the Supplementary Materials that accompany the paper.

3.5. Alluvial stratigraphy and sedimentology of recent valley fill

The recent alluvial stratigraphy of the upper Big Harris Creek basin was described in the channel banks at 21 sites shown on Fig. 2. Process zones characterized by wide valleys and entrenched alluvial channels (Groups 2–4, Table 6) possessed banks consisting of two primary sedimentary units (Figs. 7a and 8). Where both were present, the upper unit ranged from 0 to more than 150 cm in thickness (Fig. 2); it consisted of dark reddish brown to buff colored layers of massive sandy loam sediments and/or cross- or horizontally-bedded, loose sands. Its sediments contained historic artifacts, such as metal straps, indicating that the unit post-dates European settlement in the area. These sediments are therefore referred to here as legacy sediments (Fig. 7).

The upper sedimentary unit (i.e., the legacy sediment) abruptly overlies a finer-grained (clayey), dark grey to black unit along an abrupt boundary (Fig. 7a,b). The grain size of these sediments systematically decreased downward into grey (gleyed) fine-grained, silt- to clay-loamy sands, and eventually to loamy sands to gravels. Radiocarbon dates obtained on organic sediments (2 samples) and wood (1 sample) collected from along Upper Stick Elliott Creek constrained the age of the unit to between 290 +/- 30 YBP and 3760 +/- 30 YBP. It appears, then, to predate European settlement in the area, as was expected.

Channel banks along ephemeral and perennial headwater channels as well as deeply incised channels were primarily composed of relatively old, highly weathered alluvial and colluvial sediment of varying texture (Figs. 6, 7c). Although grain size variations were visible, exact depositional boundaries were typically obscured by thick soil development. An exception occurred in areas characterized by topographic depressions, particularly within the headwaters of Stick Elliott and Fletcher Creeks, where the dark grey to black, pre-settlement deposits occurred at the surface of the valley fill. These deposits varied in thickness from about 1 to 2 m.

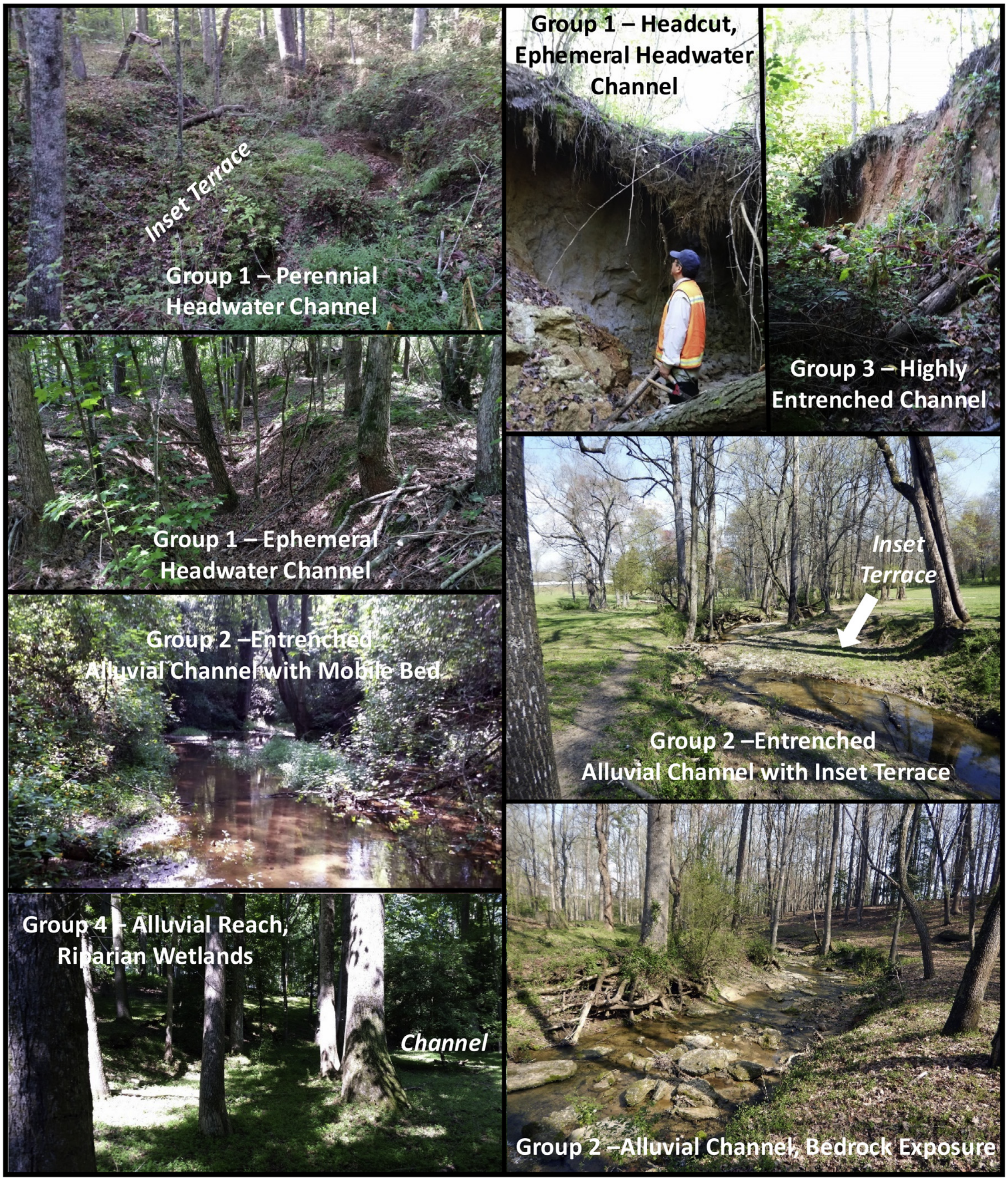


Fig. 6. Examples of selected process zone by group within the project area.

3.6. Bank erosion and erosion rates

Channel banks along process zones consisting of entrenched alluvial valleys (with or without bedrock) were extensively eroded, creating long reaches characterized by nearly vertical banks devoid of vegetation. The primary processes of erosion were corrasion (the grain by grain removal of sediment) and slab failures, resulting in the exposure of tree roots along the bank (Fig. 9). Field observations revealed that slab failures primarily occurred during the later (falling) stages of a flood, or immediately after a flood event. Thus, failed debris locally occurred between events along the base of the banks and the edge of the water during base flow conditions.

Decadal-scale bank erosion rates estimated at 19 sites using dendrogeomorphic methods ranged from 1.02 to 5.81 cm/yr; the median was 2.30 cm/yr (Fig. 10b). As noted earlier, these rates are based on the age of the tree since germination and, therefore, represent conservative (minimum) estimates of the rate of bank erosion.

4. Discussion

4.1. Comparison of suspended sediment production and transport within the region

Suspended sediment concentrations, loads, and yields have been examined within a wide range of basins in the piedmont of North Carolina by Simmons (1993) and, more recently, Simon and Klimetz (2008). Suspended sediment production and transport

Table 6
Summary of process zone types and characteristics. See Fig. 6 for photographic examples of process zones.

Reach	Valley Characteristics	Slope	Description
Ephemeral, Headwater Reaches	Relatively steep, narrow valleys; colluvium encroaches on valley floor	Relatively high (0.02)	***Group 1*** - Low-order, ephemeral channels typically found at upstream most section of the drainage network; gullies extend from channels into colluvial hillslope; entrenchment is relatively high (>2.5 m); channels may terminate in headcut; reach dominated by ongoing incision, headcut migration, and/or bank erosion; no legacy sediments present; limited sediment storage in bards or other channel features
Perennial, Headwater Reaches	Narrow, but well defined alluvial surface, with entrenched channel	Low to Moderate (0.01-.015)	***Group 1***- Low-order, perennial reach; channels entrenched several meters below valley floor; inset floodplain locally present in trench; thin layers of legacy sediments locally present on terrace surface; sediment derived predominantly from bank erosion and minor channel incision; limited sediment storage in bars and other channel features
Entrenched Alluvial Channel with Inset Terraces	Wide, well-defined alluvial valley floor	Low to Moderate (.01 - .015)	***Group 2*** - Channel entrenched 1-3 m below valley floor; well-defined inset floodplain within trench; bank often semi-vertical on side opposite of inset and composed of both pre- and post-settlement (legacy) deposits; reach dominated by bank erosion and minor channel incision; sediment storage occurs on inset terrace, within channel bars, and on valley floor
Entrenched Alluvial Channel without Inset Terraces	Wide, well-defined alluvial valley floor	Low to Moderate (.01 - .015)	***Group 2*** - Channel entrenched 1-3 m below valley floor; process zone generally found along downstream sections of a subbasin; banks are near vertical and commonly composed of both legacy and pre-settlement deposits; reach dominated by bank erosion; sediment storage occurs in relatively small bars and on valley floor
Alluvial Channel, with Bedrock Exposures	Wide to moderately wide valley floor	Moderate to high (0.15-0.2)	***Group 2*** – Entrenched channel (1-3 m) with local bedrock outcrops along channel bed; may form knickpoints that limited channel incision; bedrock areas surrounded by loose, sand and gravel; bank erosion is common, but not as extensive as along entrenched alluvial reaches; reach dominated by sediment transport with sediment storage on valley floor
Entrenched Channel with Mobile Bed	Wide, well-defined alluvial valley	Low (0.01-0.008)	***Group 2*** - Channel entrenched 3-4+ m below valley floor; channel bed prone to large changes during flood, but composed of well-defined morphologic units; banks are typically vertical, and subject to significant erosion by corrasion and with frequent slab failures; in-channel storage is high in bars, but depth of incision inhibits valley floor sediment storage; bank materials consist of both legacy and pre-settlement sediments
Highly Entrenched Channel	Variable valley width composed of both colluvial and alluvial sediments	High to moderate (0.15-0.2)	***Group 3*** - Channel entrenched 2-5 m below valley floor; trench walls, composed of relatively old alluvial deposits and saprolite, confine flow and allow for efficient sediment transport; erosion of steep trench walls is significant; post-settlement deposits limited to local terraces inset in trench, particularly along downstream reaches.
Alluvial Channel with Riparian Wetlands	Wide, alluvial valley	Low to Moderate (.01 - .015)	***Group 4*** - Channel entrenchment is limit and cut into alluvial fill; riparian wetlands with small springs border channel; bedrock close to surface, and locally outcrops in bed and banks; reaches are currently stable; moderate sediment storage in channel bars and on floodplain/valley floor.

within Big Harris Creek are substantially higher than in other catchments characterized in the region by these two investigations. Simmons (1993), for example, analyzed suspended sediment data collected at 152 gaging stations in North Carolina between 1970 and 1979. He found that the highest recorded SSC values were in agricultural and urban impacted basins, and reached a maximum of 5600 mg/L. This maximum value is well below the maximum SSC value measured for Big Harris Creek (11,081 mg/L, Table 4).

A comparison of sediment loads within the region to Big Harris Creek is complicated by differences in basin area. As a headwater catchment, the Big Harris Creek project area is substantially smaller than other monitored catchments, and would be expected on the basis of catchment size to exhibit lower sediment loads. However, sediment loads measured within the Big Harris Creek project area are some of the highest reported for the piedmont of North Carolina by both Simmons (1993) and Simon and Klimetz (2008). The maximum sediment load reported by Simmons (1993) for urban basins <25 km^2 in size (about twice the size of Big Harris Creek above BH1, 9.61 km^2) was 399 tonnes/yr within McMullen Creek, near Charlotte, North Carolina. The maximum sediment load observed for a rural basin affected by agriculture was 2813 tonnes/yr within Double Creek near Roseville (Simmons, 1993). The estimated load at BH1 in Big Harris Creek was 3895 tonnes/yr (Table 5).

Sediment yield describes the amount of sediment discharged from the catchment per unit basin area. Simon and Klimetz (2008) found that within the piedmont of the southeastern U.S., the median sediment yield was 39 tonnes/km^2/yr; the 90th percentile of unstable basins studied exhibited a mean sediment yield of 72 tonnes/km^2/yr, well below the 425 tonnes/km^2/yr estimated for BH1 within Big Harris Creek. The values provided by Simon and Klimetz (2008) are lower than those provided earlier by Simmons (1993). Simmons found that the maximum sediment yield estimated for an agriculturally affected basin within the piedmont was 154 tonnes/km^2/yr. Only Irwin Creek, a clear outlier affected by urban activities near Charlotte exhibited a sediment yield higher than estimated for Big Harris Creek (525 versus 425 tonnes/km^2/yr, respectively) (Table 5). Most urban affected watersheds examined by Simmons (1993) exhibited sediment yields of <230 tonnes/km^2/yr.

4.2. Geomorphic evolution of the drainage network

Significant differences in suspended sediment concentrations, loads, and yields were observed between the four drainages that were monitored at BH1, BH2, BHT1, and BHT2 as well as with the passive samplers (Tables 3–5). In the following sections, it is argued that these spatial differences, and the relatively high values of sediment production and transport within the Big Harris Creek basin, are related to the types and distribution of process zones within the catchment, which, in turn, reflect the basin's geomorphic responses to land-use change.

As noted earlier, process zones characterized by entrenched alluvial channels (Table 6, Fig. 7) consistently contain alluvial valley fill deposits composed to two primary units. The lower unit,

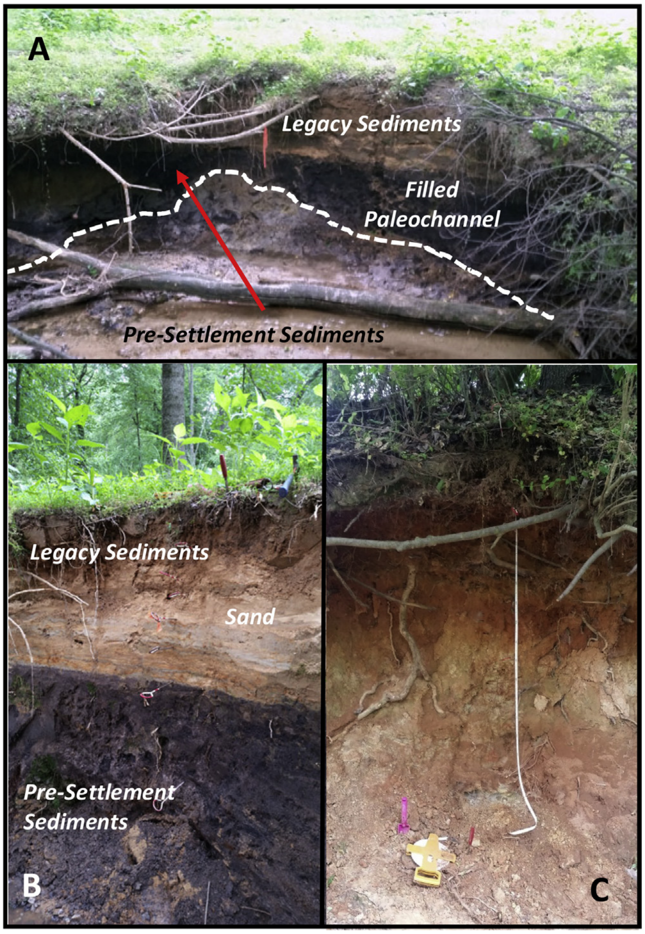


Fig. 7. Bank exposure located along entrenched alluvial channels (A) near the confluence of Stick Elliot and Fletcher Creek, and (B) upstream, along Stick Elliot Creek. Reddish brown to buff colored sediments represent legacy sediments enriched in sand-sized sediments. Dark sediments represent fine-grained, pre-settlement deposits. (C) “old” alluvial deposits that comprise upland deposits at the confluence of Stick Elliott and Fletcher Creeks.

consisting of dark colored, finer-grained, organic rich sediments, dates back to approximately 4000 YBP. The grain size and composition of this unit suggest that the hydrologic and geomorphic conditions at the time of deposition were fundamentally different from those that existed during the deposition of the overlying coarser-grained, buff colored sediments. The transition from lower to upper basin conditions was presumably related to land-use changes that occurred at the end of the 1800s and early 1900s. Historical data and landowner accounts indicate that most the previously forested basin was clearcut to grow cotton. In fact, from the late 1800s until about the late 1940s the area was one of the largest cotton producers in the U.S. The change in land-use led to several decades of severe upland erosion and valley bottom sedimentation that has been well documented throughout the southeastern U.S. (e.g., Trimble, 1974; Leigh and Price, 2006; Leigh, 2010), and that was responsible for producing what is referred to in the literature as post-settlement alluvium (or legacy sediments) (Waters et al., 2007).

The thickest and most extensive legacy deposits in Big Harris Creek were associated with process zones characterized by entrenched alluvial channels (with or without inset terraces) and entrenched channels with mobile beds (Fig. 2). These process zones possess wide valley floors that allowed for the accumulation of eroded upland sediments. In contrast, along upstream reaches, dominated by ephemeral and perennial headwater channels, legacy sediments were generally absent. However, an inset terrace composed of pre-settlement deposits locally occurred within deeply incised reaches. Large trees, dated to between 1944 and 1953, occurred on the surface of the terrace, indicating that incision in headwater areas begun during the period of extreme upland erosion (late 1800s to early 1900s), and allowed the dark-colored, pre-settlement deposits to remain at the surface of the entrenched valley floor (e.g., along Stick Elliott and Fletcher Creeks). Upland gullies that formed during the late 1800s and early 1900s, and which headed on hillslopes, were also associated with ephemeral or perennial headwater channels.

Sediment eroded during early incision of these upstream areas was transported downstream where it was delivered to the floodplain/valley floor surface, thereby burying the dark, organic rich pre-settlement deposits. The obtained dendrochronological data show that most tulip poplar trees located along Big Harris Creek germinated in the 1950s and 1960s (Fig. 10), the time that conservation practices were implemented in the basin. Given that significant deposition and reworking of sediment on the valley floor would have either killed recently planted trees, or inhibited tree germination, channel incision was likely to have begun along downstream reaches of the drainage network around the mid-1900s. Incision exposed both the legacy sediments and the older pre-settlement deposits within process zones now characterized by entrenched alluvial channels. Locally, incision was inhibited by resistant bedrock units that outcrop along the channel bed. These bedrock units, and their influence on incision, led to the development of two types of process zones: alluvial channels with bedrock exposure and alluvial channels with riparian wetlands. Legacy sediments were limited along both types of process zones.

The influence of bedrock on channel development is well illustrated by comparing channel form, and process zone type, upstream of BHT1 and BH2 (Fig. 2). The channel bed within the BH2 drainage is periodically characterized by bedrock exposures that restricted channel incision, and which lead to elevated water tables. The result was the development of a relatively wide valley floor locally characterized by alluvial channels with riparian wetlands (Figs. 2, S1). In contrast, bedrock exposures are limited along the bed of Royster Creek upstream of BHT1. Moreover, the bedrock differs from the strata that underlies BH2 in that it is comprised of more easily weathered and eroded rocks. As a result, the depth of channel incision was significant, exceeding 4 m below the valley floor, and increases upstream with distance from the axial drainage. Incision resulted in the development of a deeply incised channel (Fig. 2) characterized by a v-shaped valley that possesses steep, locally barren slopes that sluff sediment from upland soils and, at depth, saprolite, into the channel along the mid- and upstream reaches of the BHT1 drainage (Figs. 6, S1). Within these areas there is little room for sediment re-deposition and storage.

4.3. Controls on suspended sediment concentrations and loads

The recognition that legacy deposits may be an important source of sediments to a stream or river is not new. An increasing number of studies have shown that the erosion of legacy sediments can degrade water quality, aquatic habitat, and potentially, riparian biotic assemblages (Allan, 2004; Jackson et al., 2005; Bain et al., 2012; Niemitz et al., 2013; Surasinghe and Baldwin, 2014). What is significant from this study is that the geomorphic history of the basin, and the resulting legacy sediments, influenced the source and transport of SSC within a small, headwater stream.

Field observations have shown that bank erosion associated with channel incision was a significant problem within Big Harris Creek, especially along process zones associated with entrenched

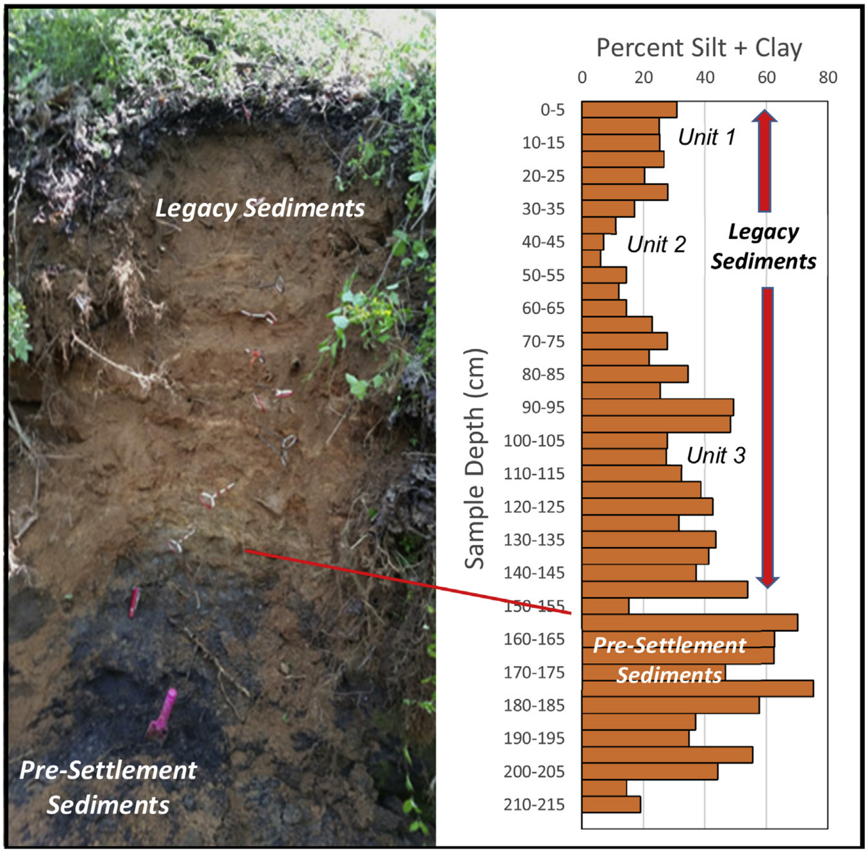


Fig. 8. Stratigraphic section measured near BH1, near the mouth of the study basin. Graph shows the finer-grained nature of the pre-settlement sediments, and the sandy nature of the legacy sediments.

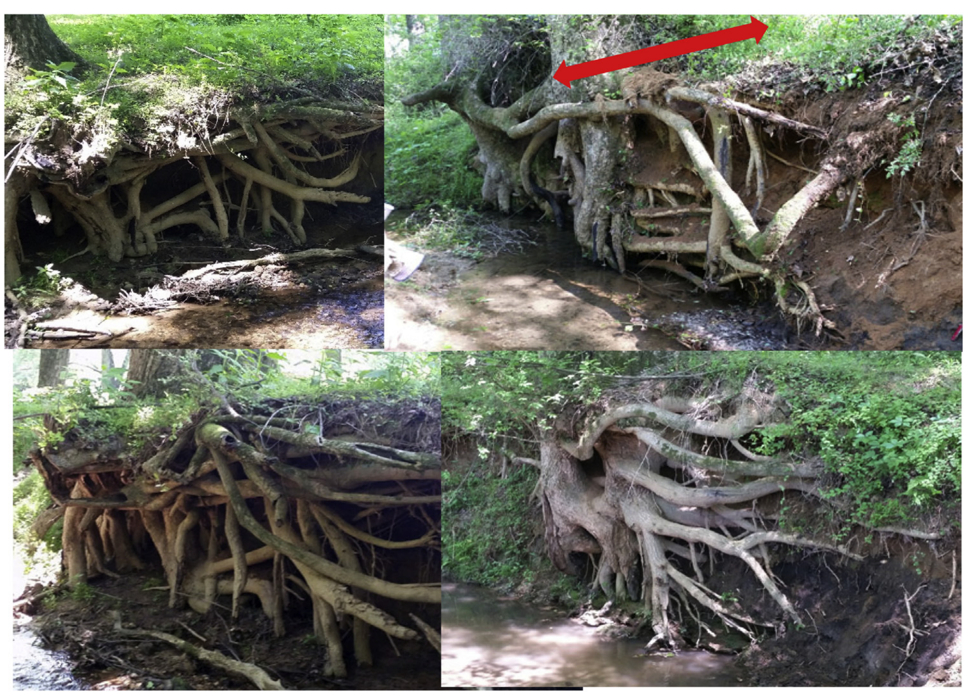


Fig. 9. Exposure of tree roots caused by bank erosion. Rates of erosion were determined by (a) dendrochronologically determining the age of the trees and (b) using the roots as a guide to the amount of erosion that has occurred since germination of the tree (illustrated by the red arrow). Bank erosion locally exceeded 3 m (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

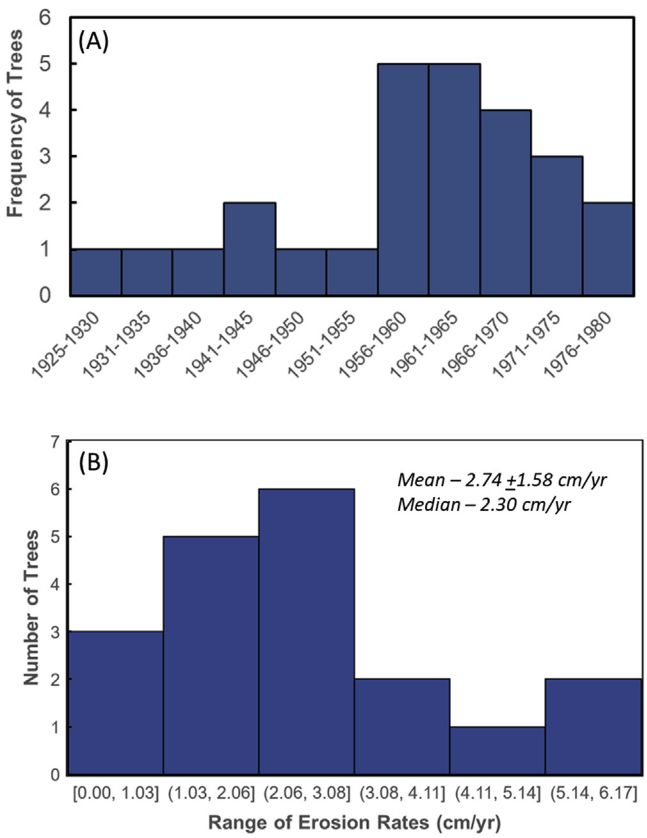


Fig. 10. (A) Histogram of approximate time of tree germination. Graph does not account for collection of tree cores at ~1 m above ground. Exact date of germination is likely to be 3–4 years prior to date shown. (B) rates of erosion based on tree age and width of exposed tree roots along channel banks. Includes trees from along Stick Elliott Creek, Upper Big Harris Creek, and the BHT1 drainage.

alluvial channels (Table 6). Erosion primarily occurred by means of corrasion (the grain by grain removal of particles) from sandier bank units, and slab failures where finer, more cohesive bank units occurred (Fig. 9). If it is assumed, for illustrative purposes, that the median rate of bank erosion (determined using dendrochronological methods, Fig. 10) was 2.30 cm/yr, the average bank height was 2.5 m and the bulk density of the bank material was 1.65 g/cm^3, 94.9 tonnes of sediment would have been supplied to the channel per linear kilometer of bank per year. Of course, bank heights, erosion rates, etc. are not consistent along the channel, and more detailed analyses are needed to refine such sediment budgeting. Nonetheless, when compared to measured sediment loads, this rough calculation demonstrates that bank erosion was a significant source of sediment to the channel. For example, if sediment was derived from both sides of the channel, the median calculated erosion rate suggests that about half of the sediment load measured in the larger drainages (BHT2 and BH1) was derived from bank erosion; within the BH2 drainage, nearly all of the measured suspended sediment load can be accounted for by bank erosion.

Given the importance of bank materials as a sediment source, the basin's geomorphic history and its resulting alluvial stratigraphy appears to be responsible for the duality in suspended sediment transport observed within the monitoring data. Bank erosion by slab failure often resulted in the accumulation of loose sediment at the base of the banks and along the edge of the water during base flow. Raindrop impacts and runoff from these deposits during precipitation was able to have delivered fine-sediments to the water column during low magnitude floods (those characterized by minimal changes in water levels). During larger events, these fine sediments could be flushed into the water before significant increases in discharge occurred. Thus, the input of bank-side sediment accounts for both the observed, highly elevated SSCs during low magnitude floods, and the noted hysteresis effects in which rapid rises in SSC (Fig. 5) occurred before significant increases in discharge. Most of this sediment was likely to have been derived from the pre-settlement deposits because (1) their finer-grained and more cohesive nature allowed these deposits to more frequently fail by slab failure, and (2) more runoff cold be generated from these finer-grained sediments during low intensity precipitation than from failed materials derived from the sandier, more permeable legacy sediments. Some of the sediment was also derived from cattle crossings where cows loosened the bank sediments and moved it to the edge of the water. Importantly, because discharge in the channel was limited during these low magnitude floods, significant increases in SSC did not require large inputs of fine sediment.

During higher magnitude floods, these fine-sediments would also be delivered to the channel during the very early stages of the flood. However, as these events progressed, and stream discharge increased, additional sediments were required to increase SSC. Inspection of the samples collected during these floods showed that not only was SSC higher, but the sediments in transport were dominated by larger, sand-sized particles. These sediments were presumably derived from the erosion of loose, non-cohesive legacy deposits exposed in the channel banks, and from upstream gullies associated with ephemeral and perennial headwater reaches.

Much of the variability in SSC during these large floods can be attributed to clockwise hysteretic loops. Clockwise hysteresis is indicative of the "first-flush phenomena" in which easily eroded sediments result in rapid increases in SSC during the early phases of a flood. SSC then decreases before the peak in discharge is reached as the availability of loose, easily mobilized sediment declines (Williams, 1989). In Big Harris Creek, clockwise hysteresis during the larger floods (those characterized by a direct relationship between SSC and discharge, Fig. 4) supports the argument that suspended sediment transport was influenced by the availability of easily mobilized sediment from failed bank material as well as coarser grained sediments from legacy deposits and gullies.

The hypothesized difference in sediment sources between small and moderate to large floods is consistent with the regression analysis (Equation 2) that found, using data from BH1, that SSC varied as a function of average rainfall intensity and total event precipitation. Events of higher intensity and more rainfall were capable of mobilizing and delivering more sediment to the water column than lower intensity storms characterized by less rainfall that were unable to transport sediment from the pre-settlement deposits to the channel, or to generate the overland flow required for gully and/or bank erosion.

4.4. Spatial variations in suspended sediment loads

Both the ISCO (Tables 3–5) and passive U59B sampler (Fig. 3) data revealed that sediment concentrations, sediment loads and sediment yields varied spatially within the Big Harris Creek project area. The highest sediment yield was observed at BHT1. It was several times higher than the sediment yields observed in the drainages monitored by BH1, BHT2, and BH2 (before clearcutting) (Table 5). Differences in sediment yield may be accounted for in part by differences in land-use/landcover. The Royster Creek subbasin (monitored by BHT1), which exhibits the highest sediment yields, also exhibited the highest percentage of row crops in the project area, and the lowest percentage of forested terrain (Table 3). However, sediment yields also vary with the nature of the process zones created in response to region's changes in land use. For example, in contrast to the other subbasins, BHT1 is dominated by a highly-entrenched channel that possesses a v-shaped valley with steep, locally barren slopes (Fig. S1). Field observations showed that sediment was extensively eroded from the slopes that formed the margins of the channel, and was transported into the channel along the mid- and upstream reaches of the BHT1 drainage network. The influx of sediment from the trench walls was accompanied by the influx of sediment from gullies and bank erosion associated with ephemeral headwater channels.

While sediment yields within BHT1 were relatively high, total sediment export (load) from the basin was relatively low because stream flow was limited by its small catchment area (Table 5). The BHT2 drainage area exhibited the highest sediment loads (Table 5). While it encompasses only about 33% of the watershed, it contributed 57% of the calculated sediment load for the entire project area. Land use within the subbasin during monitoring was dominated by forest (56.7%) and pasture (32.3%) lands, which were unlikely to have generated significant quantities of upland sediment. Rather, the relatively high rates of suspended sediment generation and transport from BHT2 were probably related to gully systems associated with ephemeral and perennial channels in the subbasin's most upstream reaches (which encompass about 40% of the basin)(Figs. 2, S1). A particularly large gully characterized by an ~5 m high headcut and steep, eroding sides was present within Stick Elliot Creek. High sediment loads were also related to the widespread occurrence of entrenched alluvial channels that were bound, in part, by legacy sediments containing loose, non-cohesive sand-sized sediment (Fig. 7a,b). The dendrogeomorphic data, for example, indicated that bank erosion along entrenched alluvial channels was significant, particularly within the BHT2 subbasin. The fact that more than 60% of the drainage network within the BHT2 catchment was composed of entrenched alluvial channels (Fig. S1) locally characterized by easily eroded legacy deposits >50 cm in thickness (Fig. 2), shows that these deposits are a significant sediment source. Unfortunately, the existing dataset does not allow for a direct, quantitative analysis of the importance of the thickness and extent of legacy sediments on sediment loads, relative to other sediment sources (e.g., gullies). However, geochemical fingerprinting studies are currently being conducted to more fully address the source issue. The point here is that the stratigraphy of the bank deposits, including the thickness and extent of the basin's legacy sediments, influenced (1) the relationships between discharge and SSCs, (2) total sediment loads exported from the basin/subbasins, and (3) sediment yields.

On March 2, 2016, a large amount of fine-grained (< 63 μm) sediment was observed on the bed of the channel at and upstream of BH2 during the collection of water samples at the site. The influx of fine sediment was due to upstream, localized clearcutting associated with development. The statistically significant increase in concentrations, combined with the observed deposition of fine sediment on the channel bed, indicates that tributary catchments remain highly sensitive to renewed upland land-use change.

5. Conclusions

Water quality monitoring data were combined with geomorphic and stratigraphic data to develop a conceptual model of the sources and transport of suspended sediment within the headwaters of Big Harris Creek. The source and transport of suspended sediment differed between relatively low magnitude floods (characterized by minimal changes in water levels) and moderate to high magnitude floods. During low intensity, low volume precipitation events, characterized by minimal overland flow, channel-edge sediment associated with mass wasting (slab failures) and cattle crossings was quickly delivered to the water column, particularly from fine-grained pre-settlement deposits located at the base of the banks. During these low magnitude floods, variations in SSC exceeded 1 to 2-orders of magnitude, and reflected variations in sediment supply, rather than differences in channelized flow. During higher magnitude floods, direct relationships between SSC and discharge existed within the larger subbasins (BH1, BHT2, Fig. 4). Fine-sediments were also delivered to the channel during the very early stages of these floods, creating clockwise hysteretic loops (through a first-flush process). However, as these events progressed, additional sediment, particularly from the erosion of legacy sediments and gullies, was delivered to the channel. Thus, the distinction between low and moderate/high magnitude floods could be defined on the basis of SSC-discharge relationships, and varied between the monitoring sites. The observed differences in SSC between low and moderate to high magnitude floods complicates the assessment of water quality changes resulting from stream restoration projects, and suggests that comparisons will need to differentiate between these two populations of runoff events.

While the Big Harris Creek study area was a small, headwater catchment, significant spatial difference in SSC, sediment loads, and sediment yields were observed. These spatial variations appear to be related, in part, to: (1) geographical differences in the basin's geomorphic responses to land-use change following European settlement, and the type of process zones that were created, (2) the distribution of legacy sediments within the process zones, and (3) the ability of the process zones to produce, transport and store sediment.

Acknowledgments

The collection of nearly six years of water quality data was aided by a large number of students and research scientists. We thank all of them for their help, particularly Ken Walton, Jacob Sinclair, and Danvey Walsh. Funding for the project was provided in part by the North Carolina Division of Mitigation Services (NCDMS) and the Whitmire Endowment at Western Carolina University. We are grateful to both for their support. We also thank two Anonomous reviewers for their highly constructive comments.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ancene.2018.12.002.

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Further reading

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