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ORIGINAL ARTICLE

Changes in stream morphology protected by best management practices under effects of upstream disturbances

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Abstract
Stream channels are usually more stable in forested watersheds. However, intensive land disturbances in forested watersheds may disrupt the balance between flow and sediment supply, and result in variations in stream morphology even in the presence of well-designed best management practices (BMPs). This study evaluated the impacts of upstream land disturbances on downstream stream morphology where streamside management zones (SMZs) were present in two small adjacent watersheds in Auburn, Alabama, USA. Field surveys including the measurements of channel cross sections at bankfull stage were conducted at 12 survey sites over an 18-month period. Both in-stream sediment deposition and erosion were observed downstream of the disturbed areas in the study watersheds. As a result, channel cross sections exhibited very dynamic patterns changing frequently over short time periods. Overall, the dominant process was in-stream deposition in both watersheds due to large amount of sediment delivered from upstream-disturbed areas. In spite of the dynamic patterns of the channel cross sections in response to upstream disturbances, the commonly used parameters of Rosgen stream classification remained stable, suggesting that the upstream disturbances did not lead to changes in stream classification. In general, bank erosion was not observed. Therefore, it is likely that SMZs in each watershed were sufficient to stabilize streambanks by hindering in-stream bank erosion. Moreover, the poorly designed BMPs such as silt fences and straw bales near the disturbed area seemed insufficient to balance the variations in sediment supply under the impacts of upstream disturbances. This study emphasized that proper installation and continuous monitoring of BMPs should play a critical role on watershed management. It also indicated that watershed management should be handled using a holistic approach with well-distributed BMP applications within the entire watershed.

Keywords Upstream disturbances · Erosion · Deposition · Streamside buffer zones · Stream morphology

Introduction

Erosion and sediment transport are typically not significant processes in forested watersheds because of the positive effects of vegetation in breaking up the kinetic energy of rainfall, reducing overland flow and trapping sediment (Corbett et al. 1997; Nelson and Booth 2002; Hassan et al. 2005; Chang 2006). However, land disturbances can influence water and sediment discharge even in forested watersheds since they may have severe impacts in fluvial systems (Bilby et al. 1989; Doten et al. 2006; Boix-Fayos et al. 2007). Silvicultural activities, intensive agriculture practices, overgrazing and conversion of forested lands to other land use/land cover (LU/LC) may alter the balance between flow and sediment, and lead to accelerated erosion and channel aggradation (Liébault et al. 2005; Sapkale 2014). Conversion of forested lands to other land uses, especially urban, can increase the magnitude and frequency of peak flows and, therefore, affect stream morphologies by changing channel dimensions, types of bed materials, and riparian vegetation (Trimble 1997; Galster et al. 2008).

Several studies revealed the negative effects of land conversion and forestry activities on stream channel morphologies. Ralph et al. (1994) examined stream channel morphology in managed and unmanaged basins in western

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Washington, and found that intensive harvest operations impacted channel habitat. In another study, Knox (1977) monitored the influence of land conversion in Platte watershed of southwestern Wisconsin, and found that land conversion resulted in major changes in channel morphology. Moreover, Price and Leigh (2006) observed the effects of forest conversion in southern Blue Ridge Mountains, and found that the conversion caused significant changes in bankfull width/depth rations, particle size and baseflow wetted widths. The negative effects of disturbances such as logging, thinning, and site preparation in forested watersheds on stream morphology can be mitigated using best management practices (BMP). Best management practices are mainly designed to guide landowners and forest practitioners to conserve water quality and soil during forestry activities (Lee et al. 2012). Even though BMP guidelines differ by state in USA, they usually present similar prescriptions (Cristan et al. 2016). Best management practices include buffer strips along the streams, proper forest-road construction, loading decks, skid trails, disposal of contaminants, site preparation, and stream crossings. When these approaches are appropriately implemented, BMPs can address water quality issues in forested watersheds (Liu et al. 2017). As a frequently implemented type of forestry BMP, a streamside management zone (SMZ) is a vegetated strip of land comprised of trees and other vegetation along a stream or other body of water such as lakes (Simpson 2002). Streamside management zone are maintained for their effectiveness in trapping sediment, maintaining sheet flow, preventing concentrated flow (Ward and Jackson 2004), controlling stream temperature (Moore et al. 2005), and stabilizing streambanks (Naiman and Decamps 1997).

While land disturbances are known to change the balance between sediment entering and leaving the streams leading to deterioration in stream water quality and alterations in stream morphology (Liébault et al. 2005; Boix-Fayos et al. 2007; Sapkale 2014), BMPs could be very efficient in protecting streams against such disturbances (Vowell 2001; Hutchens et al. 2004; Grace 2005). However, localized, often temporary land disturbances near or around the headwaters may reduce or offset the benefits gained by downstream BMPs (Sponseller et al. 2001; Cavus et al. 2017) since they can affect the hydrologic connectivity between upstream and downstream waters (Hall et al. 2011). As an example to this, Cavus et al. (2017) monitored two small adjacent watersheds (named west and east watershed) near Auburn, Alabama, USA between 2014 and 2015. The goal was to observe the impacts of upstream disturbances on downstream sediment load under the presence of SMZs. Upstream disturbances consisted of earthwork to enlarge and deepen two ponds located at the headwaters of these two watersheds and construct a residential playground. The study showed that upstream land disturbances, where BMPs are not present or are inadequate, could severely influence downstream flow regime and water quality regardless of the presence of the downstream BMPs (Cavus et al. 2017). It is also likely that those upstream disturbances could lead to changes in downstream stream channel morphologies in these watersheds (Nelson et al. 2006; Boix-Fayos et al. 2007).

Urbanization in upstream parts of a watershed can adversely affect downstream stream channel morphology. This is because increase in impervious areas following urbanization would result in increased speed and volume of overland flow, which can cause channel erosion and consequently change the morphology of the streams (Hassan et al. 2005; Schoonover 2005; Nelson et al. 2006). Moreover, streams may also undergo geomorphic changes following the deposition of sediment transported from the urbanizing areas (Doll et al. 2002; Boix-Fayos et al. 2007). To our knowledge, research on the impacts of urban activities on downstream morphology of forested watersheds has been limited in the southeast Piedmont region of USA, which has experienced and continues to experience rapid land conversion because of the steep increase in the regional population (US Department of Agriculture 2015). Due to rapid urbanization and land conversion in the region, the concern on the sedimentation and channel instability has increased (Hardison et al. 2009; Franzluebbers et al. 2000; Schoonover 2005; Napton et al. 2010; Kara et al. 2014). The overarching goal of this study was to assess the impacts of upstream urban disturbances on downstream stream channel morphology where SMZs were present, and to comprehend the role of downstream SMZs in stabilizing stream banks in the presence of the upstream disturbances, in two small watersheds in Alabama, USA. We hypothesize that upstream urban disturbances could alter downstream channel morphology even in the presence of well-designed and maintained downstream BMPs, and these morphological responses would be spatially variable.

Materials and methods

Study site

This study was conducted on the Mary Olive Thomas Demonstration Forest (MOT) near Auburn, AL, USA (Fig. 1). The 162 ha MOT has been managed by Auburn University's School of Forestry and Wildlife Sciences since it was given as a gift to the school in 1984. Auburn is located within Piedmont upland district and East Gulf Coastal Plain, while the MOT site is on a transition zone from a Piedmont upland to a bottomland. The dominant soil types, Pacolet and Toccoa, which are typical of the Piedmont plateau, are fairly productive for the forests (McNutt et al. 1981). Study region comprises a lower package of metagraywacke schist and

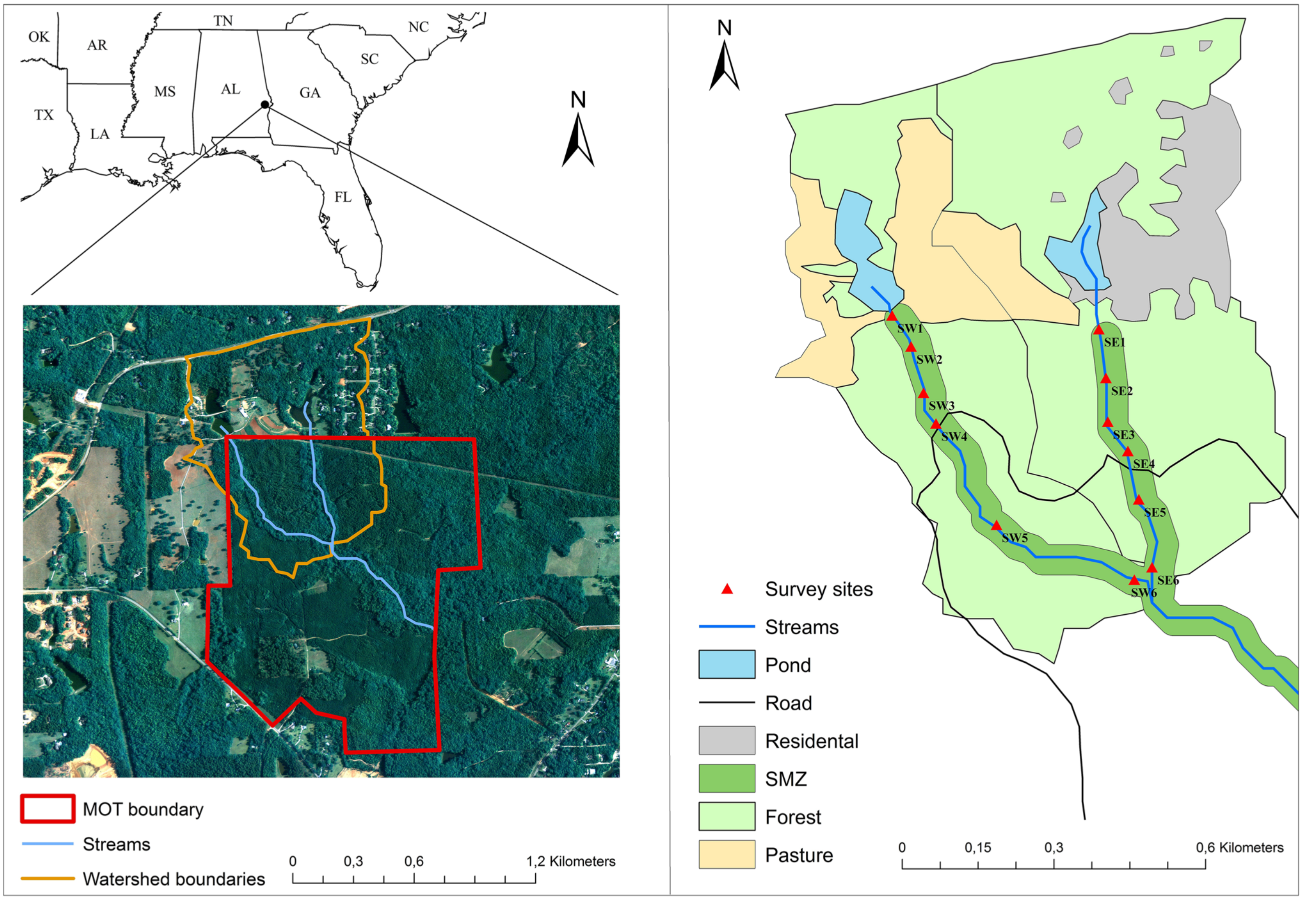

Fig. 1 Location of Mary Olive Thomas (MOT) (left), and land use/cover map of the study watersheds (right)

gneiss, and an upper package of kyanite–staurolite schist, graphitic schist, and quartzite (Raymond et al. 1988). While the south of the Auburn region sits on the coastal plain with sandy soil, north parts of the region have much more rugged topographies (AWWB 2011). Study region near MOT contains some sharp peaks and sudden drops of elevation (Neilson 2016). The lower slopes along the streams within MOT likely attain much of their original soil because these areas were not cleared because of the rocky formations in these zones (Alabama Cooperative Extension System 2009). The soils in the study area fall into hydrologic soil group B owing to their moderate infiltration rate and moderate rate of water transmission (https://websoilsurvey.sc.egov.usda.gov). The RUSLE-K factor is an indicator of soil erodibility, and it describes the susceptibility of soils to sheet and rill erosion. Its values range from 0.02 for the least susceptible soils to 0.69 for the most susceptible (Goldman et al. 1986). The average RUSLE-K value of the soils in the study area is 0.17. (https://websoilsurvey.sc.egov.usda.gov). Average slope is less than 6%, but steep slopes also occur in certain parts of MOT. Loblolly pine (*Pinus taeda* L.) plantations, and natural longleaf pine (*Pinus palustris* Mill.) stands are the dominant stand types in MOT (MacKenzie 1999). Based on data from 1980 to 2010, average annual rainfall in the study area is 1340 mm of which ~ 50% occurs from April to September, while average daily temperature is 17.3 °C (http://www.prism.oregonstate.edu, accessed on November 7, 2016).

Study design

Two small adjacent watersheds, named west watershed (W_W) with an area of 37 ha and east watershed (W_E) with an area of 50 ha, were chosen in MOT. The main creeks in each watershed were buffered with SMZs (Fig. 1), which are covered by deciduous species such as white oak (*Quercus alba*), water oak (*Quercus palustris* Muenchh.), sweetgum (*Liquidambar styraciflua*), yellow poplar (*Lirodendron tulipifera L.*), and flowering dogwood (*Cornus florida* L.). The SMZs in the study watersheds are wider than 10 m required for both perennial and intermittent streams in Alabama (Alabama Forestry Commission 2007). Delineation of the study watersheds and stream network were completed using a 10-m digital elevation model (DEM) with

ArcSWAT (Srinivasan 2005). Elevation ranges from 180 to 230 m across the two study watersheds. LU/LC map of the study area was created using ArcGIS (Fig. 1). An aerial photo taken in 2014 was used as the base layer for digitizing. Northern part of W_W, which is privately owned, is mostly pasture and forest with a pond in the middle (Fig. 1). North of W_E, which is also privately owned, is mostly residential area and forest with a pond in the middle. The middle and downstream sections of both watersheds are mainly forested (Fig. 1). The SMZ of W_W was partially harvested in early 2009 to analyze the effectiveness of SMZs in trapping sediment (Kara et al. 2014).

During the study period, there were some upstream construction activities around the ponds in W_W and W_E (Fig. 1). There was no exact information about the onset of these activities because of the limited access to the area. During the initial data collection in February 2014, some construction activities around the pond in W_E were noticed, while no land disturbance upstream of W_W was imminent around that time. Land disturbances in the upstream sections of W_W were first observed after 1 month following the disturbances observed in W_E. Within the construction sites, BMP_S such as straw bales and silt fences, were installed by the landowners in the headwaters of the watershed to control or at least minimize the sediment load from the disturbed area. They were placed south of the ponds, just upstream of where the SMZs begin in MOT (Fig. 1). The upstream land disturbance activities ceased in early spring of 2015. Note that no SMZs were present within the private properties (i.e., north of W_W and W_E) (Fig. 1), thus this study did not aim to examine the effectiveness of SMZs at trapping sediment contributed by sheet flow from the disturbed area. Instead, the focus was more on the efficacy of the SMZs downstream of these urban disturbances.

Twelve survey sites, six in each watershed, were selected to frequently collect cross-sectional data, and observe the impacts of upstream disturbances on streams channel morphology. The straight sections of the reaches having bankfull stage indicators and not containing pools were preferred as the locations of survey sites. The sites were named from upstream to downstream as S_{W1},…, S_{W6} in W_W, and S_{E1},…, S_{E6} in W_E (Fig. 1). The length of the reaches between each sites varied since we tried to have more survey sites close to the disturbed area (Fig. 1) (Table 1). It should be noted that the upstream of S_{W1} and S_{E1} were private land, thus, no site was selected within these areas due to the limited access (Fig. 1).

Solinst Levellogger Gold Model 3001 pressure transducers were installed at sites S_{W1}, S_{W3}, S_{W6}, S_{E1}, S_{E3}, and S_{E6} to record flow depth at 15-min intervals, which were later converted flow discharge time series using stage-discharge curves developed for each site. Water samples were also collected at those sites during every significant rain event (forecasted rainfall depth > 12.7 mm = 0.5 in). Using the 2540 total suspended solids method, total suspended solids (TSS) concentrations of the water samples were calculated (Rice et al. 2017). These concentrations were utilized for the prediction of sediment load using the LOADEST software based on streamflow data during the study period (US Geological Survey (USGS) 2014). More details on hydrology and sediment sampling/calculations can be found in Cavus et al. (2017).

Table 1 Length and slopes of the reaches

Reach	Average slope (%)	Length (m)	Reach	Average slope (%)	Length (m)
S_{W1}–S_{W2}	1.4	125	S_{E1}–S_{E2}	2.4	125
S_{W2}–S_{W3}	2.1	140	S_{E2}–S_{E3}	1.2	125
S_{W3}–S_{W4}	2.7	125	S_{E3}–S_{E4}	1.1	105
S_{W4}–S_{W5}	1.3	240	S_{E4}–S_{E5}	2.2	140
S_{W5}–S_{W6}	1.4	280	S_{E5}–S_{E6}	1.6	140

Sediment yield, which is the amount of sediment leaving the watershed outlet over a specific time, was estimated for the most downstream survey sites (i.e., S_{W6} and S_{E6}) over the study period using the LOADEST predictions. Furthermore, the net sediment deposition in each reach was divided by the channel surface area to estimate the average aggradation/degradation depth in each reach. Channel surface areas were calculated based on the bankfull width of cross sections at the survey sites and the length of the reaches. For example, bankfull widths for S_{W1} and S_{W2} were averaged and then multiplied with the distance between S_{W1} and S_{W2} to have an estimate of the surface area for the reach S_{W1}–S_{W2}.

In-stream erosion/deposition calculations

During the measurements of stream cross sections at bankfull stage, standard topographic survey methods were followed using permanent site marking stakes, a string line and level, a measuring tape, engineering survey flags and a depth rod (Harrelson et al. 1994). A horizontal measuring string was first established across the channels between permanent end point markers, so that they do not wash out over time. The measuring tape through the string line was placed to read distances in which depth readings were recorded. Depth readings were taken using a rod at 20 cm intervals. The cross section measurements were repeated through time following the rain events larger than 2.54 cm (1 in) to observe morphological changes in time. Based on the previously collected data on flow response following the rainfall events in the study area, we deemed events larger than 2.54 cm as significant enough to cause changes in stream morphology.

Cross-sectional data were plotted on grid paper using a scale of 1:20 to calculate the volume of deposited and eroded sediment over time at each survey site. Deposited and eroded areas in a cross section were traced separately since a survey site may be exposed to both erosion and deposition simultaneously (Fig. 2). The calculated areas of erosion/deposition at each survey site were then used to predict the volume of eroded/deposited sediment at each reach. For instance, to calculate the total volume of deposited and eroded sediment between S_{W1} and S_{W2}, the total deposited and eroded area over time at S_{W1} and S_{W2} were first calculated, and then averaged. The averages of eroded and deposited areas were then multiplied with the distance between S_{W1} and S_{W2}. This process was repeated between each survey site from upstream to downstream to estimate the volume of in-stream erosion and deposition at each reach. In-stream covers the entire cross-sectional area up to the bankfull stage, including the stream bed and the banks. The difference between the volume of deposited and eroded sediment between each survey sites, called 'net sediment deposition', was calculated to have an idea on the dominant fluvial process at each reach. We assumed that when the net sediment deposition in a reach is less than zero, erosion is the dominant process. Similarly, when the net sediment deposition is greater than zero, the dominant process is assumed to be sediment deposition.

The cross-sectional measurements at the survey sites also provided us an opportunity to estimate the volume of streambank erosion and deposition at each reach over time. Analysis on streambank erosion is important since streambank erosion is known as a major source of sediment transported in streams (Trimble 1997). Since one of the functions of SMZs is to stabilize streambanks, determining the extent of streambank erosion caused by upstream disturbances would be useful. The same method described for instream erosion/deposition was followed for the estimation of streambank erosion/deposition; except we only used the readings from the streambanks (i.e. streambeds were excluded). Similar to the effort described in the previous paragraph to identify the dominant instream fluvial process, 'Net sediment deposition' from the streambanks described the dominant process effective on the streambanks at each reach of W_W and W_E.

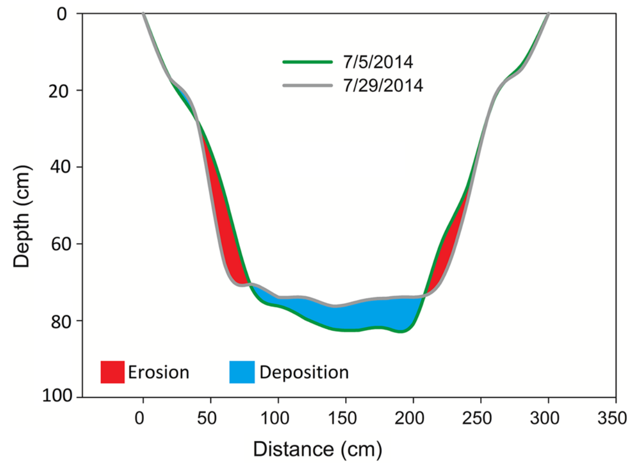

Fig. 2 Sediment deposition and erosion at T_{E5} from 7/5/2014 to 7/29/2014

Stream classification

Based on the Rosgen classification system (Rosgen 2001), streams were classified to understand the stream conditions and response of the stream channels to the upstream disturbances. The Rosgen classifications of the study streams were further examined by comparing them to references streams of this region (Brantley et al. 2013). The Rosgen classification system uses bankfull discharge dimensions for measurements. The characteristics including channel type (single or braided), entrenchment ratio, width to depth ratio, sinuosity, slope ranges and median size of bed material were characterized for the classification of the streams. Stream bed materials were documented by quantitative description of the bed material (pebble count) (Wolman 1954), and then the median particle sizes (D_{50}) were determined for both streams. Channel dimensions (bankfull area, bankfull width, bankfull mean depth, flood-prone width, width to depth ratio and entrenchment ratio) and bank height ratio (BHR) of both streams were also measured/calculated to estimate the degree of channel incision (Rosgen 2001).

Results

In-stream erosion and deposition

Cross-sectional data were collected at the survey sites after significant rain events (> 25.4 mm) from 3/31/2014 to 7/26/2015. Total eight cross section measurements were taken at each of the survey sites S_{W1}, S_{W4}, S_{W6}, S_{E1}, S_{E4} and S_{E6} during this period. The sites S_{W2}, S_{W3}, S_{W5}, S_{E2}, S_{E3}, and S_{E5} were each surveyed six times. These sites in the latter group were added later to the list since it was believed that more survey sites were needed to obtain a better picture of the sediment erosion and deposition dynamics.

Both West and East stream channels exhibited a dynamic pattern. Significant in-stream erosion and deposition were observed at most of the survey sites in W_W and W_E in short time periods during the study (Figs. 3, 4). It is evident that excess amount of sediment entered to the study streams as a result of the upstream disturbances, and depending on the magnitude of rain events and longitudinal slope, these sediments deposited or transported between the reaches (Figs. 3, 4). Average sediment concentrations entering the forested area from the disturbed sections were 647 ± 12.1 mg/L at S_{W1}, and 431 ± 15.5 mg/L at S_{E1}. The patterns of net

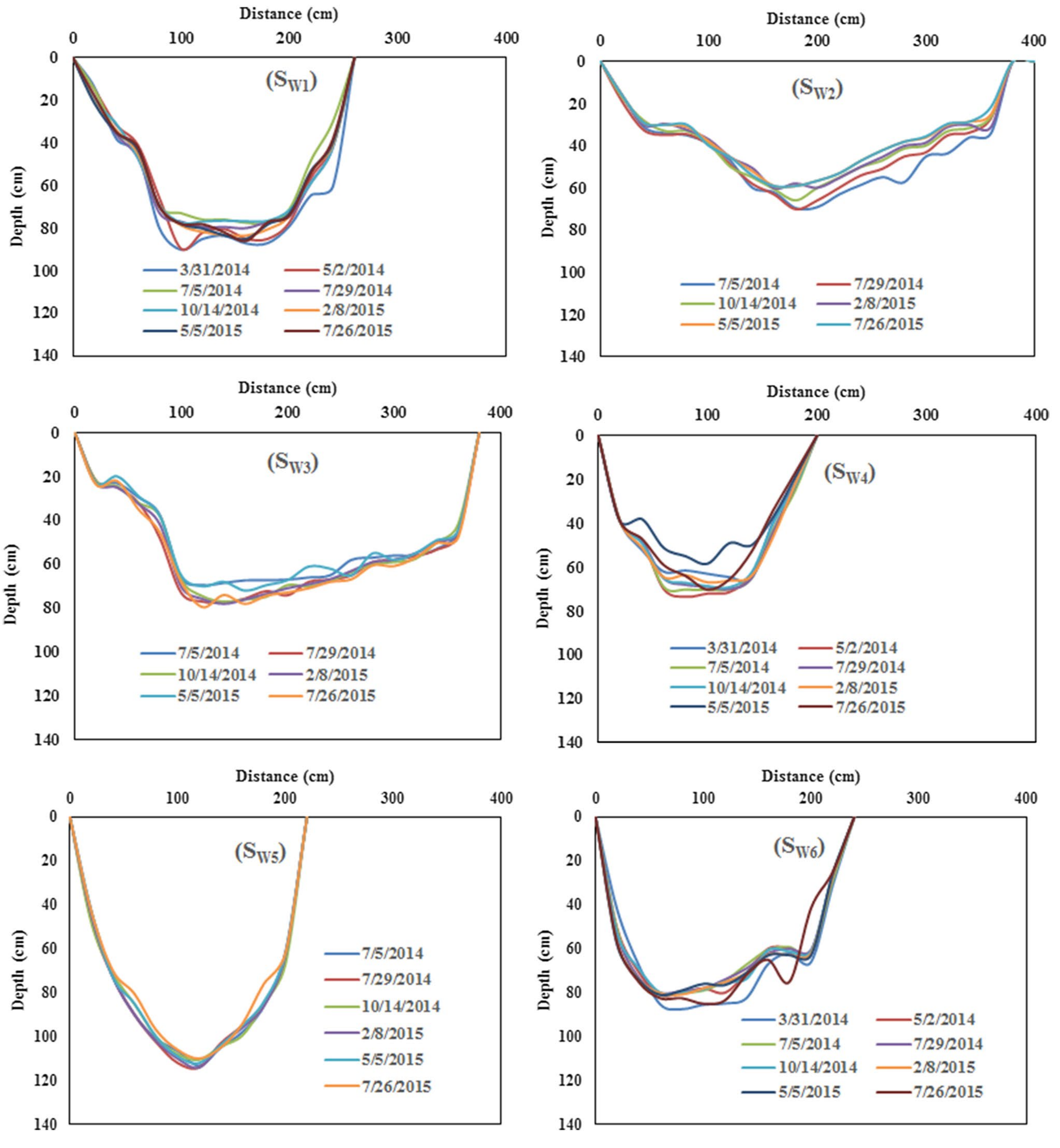

Fig. 3 Changes in cross sections at the survey sites over time at S_{W1}, S_{W2}, S_{W3}, S_{W4}, S_{W5} and S_{W6}

sediment deposition varied between the reaches in both watersheds (see Table 2; Fig. 5). In-stream deposition evidently exceeded the in-stream erosion among all of the survey sites in the West stream, suggesting that in-stream deposition was the dominant process in all reaches in W_W (Table 2; Fig. 5). Although in-stream deposition was the dominant process between some of the survey sites in the East stream channel, the two downstream reaches were exposed to in-stream erosion rather than in-stream deposition (Table 2; Fig. 5).

The predicted sediment inputs to the West and East stream channels between the most upstream and downstream survey sites (i.e., S_{W1}–S_{W6} and S_{E1}–S_{E6}) over the study period, calculated as sediment yield at the watershed

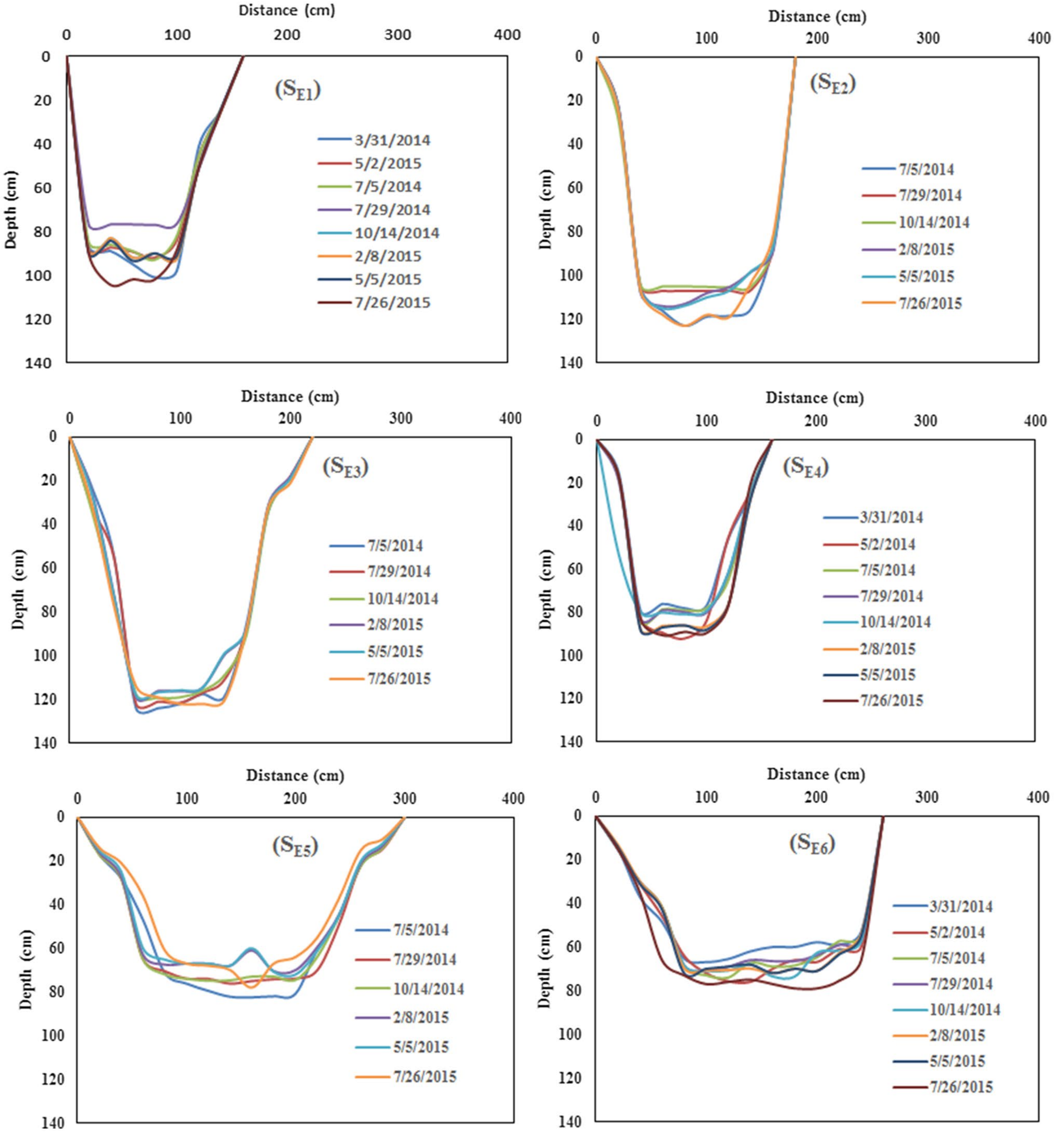

Fig. 4 Changes in cross sections at the survey sites over time at S_{E1}, S_{E2}, S_{E3}, S_{E4}, S_{E5} and S_{E6}

outlet + net instream sediment deposition, were 215.4 tons and 207.2 tons, respectively. In terms of volume, this is equivalent to 81.3 m^3 for the West and 78.2 m^3 for the East stream (assuming density of sediment as 2.6 t/m^3) (Table 3). Sediment yield over the study period from W_W was lower than the sediment yield from W_E (Table 3). However, the net sediment deposition during the study period was greater in the West stream channel compared to the sediment deposition in the East stream channel (Table 3). When the entire streams lengths between the survey sites are considered, these net sediment depositions correspond to 24 mm and 10 mm aggradation in the West and East stream channels, respectively (Table 3). Our data also suggest that sediment concentrations, and amount of in-stream erosion and

Table 2 In-stream deposition and erosion over the study period across the reaches

Reach	In-stream deposition (tons)	In-stream erosion (tons)	Net sediment deposition (tons)[a]	Reach	In-stream deposition (tons)	In-stream erosion (tons)	Net sediment deposition (tons)[a]
S_{W1}–S_{W2}	96.2	41.4	+54.8	S_{E1}–S_{E2}	49.8	39.8	+10.0
S_{W2}–S_{W3}	96.8	63.2	+33.6	S_{E2}–S_{E3}	49.4	32.2	+17.2
S_{W3}–S_{W4}	59.5	54.0	+5.5	S_{E3}–S_{E4}	43.4	17.4	+26.0
S_{W4}–S_{W5}	136.6	83.1	+53.6	S_{E4}–S_{E5}	50.8	58.6	−7.8
S_{W5}–S_{W6}	120.7	85.8	+34.9	S_{E5}–S_{E6}	65.5	66.8	−1.3
Total	509.9	327.4	+182.4		258.9	214.7	+44.2

[a](+) dominant process is 'deposition', (–) dominant process is 'erosion'

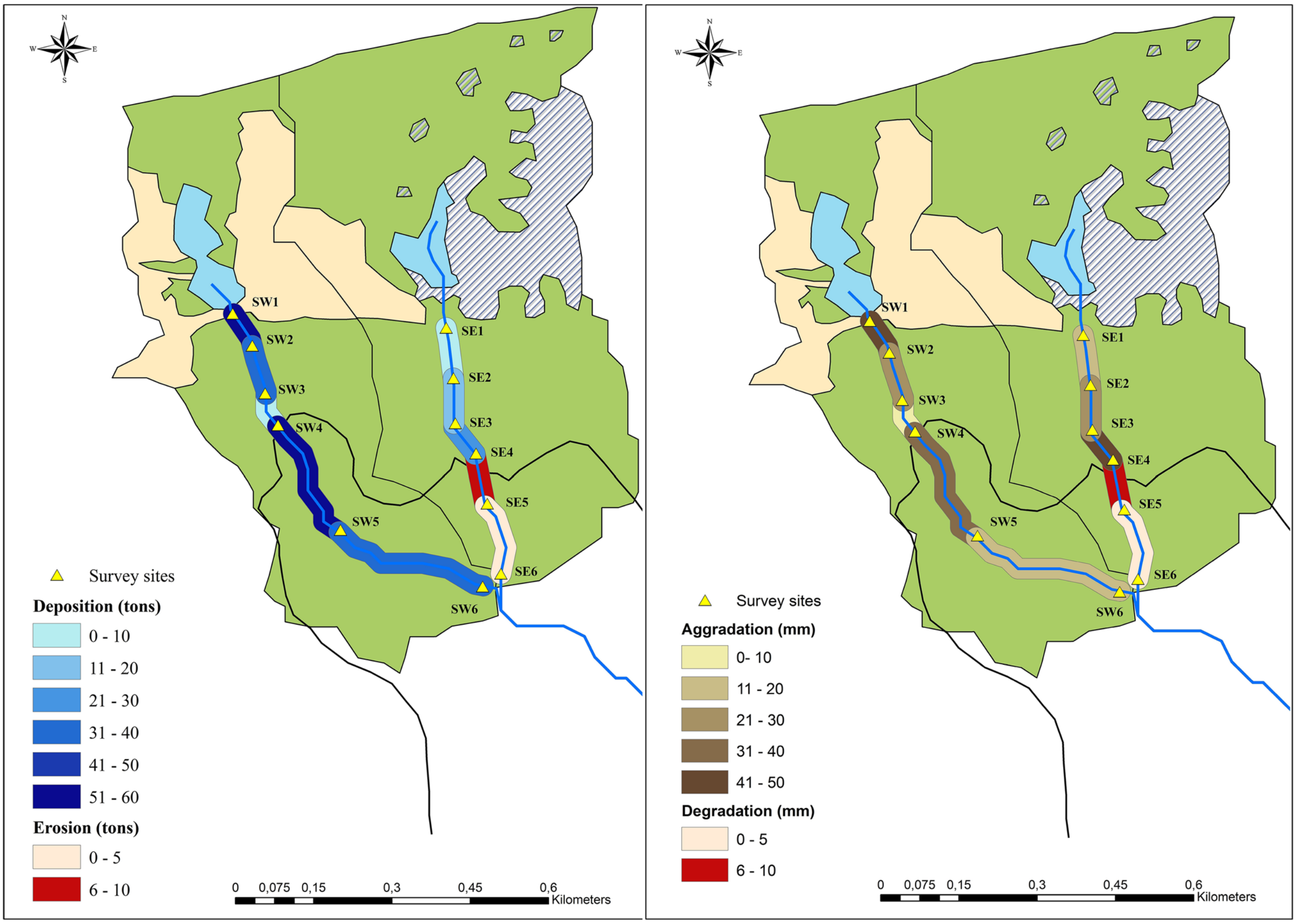

Fig. 5 Dominant sediment transport processes (left) and the aggradation/degradation depths (right) in watersheds W_W and W_E

deposition decreased following the completion of the construction activities.

Streambank erosion/deposition

The dominant processes on streambanks between the survey sites in each watershed can be seen in Fig. 6. Approximately 143 tons of sediment was deposited, and 106 tons of sediment was eroded on and from the streambanks of the West stream channel during the study period. This suggests that 28% of in-stream erosion and 32% of in-stream deposition were contributed by the streambanks. On the other hand, streambank erosion and deposition in the East stream over the study period were 117 tons and 99 tons, respectively, indicating that 38% of in-stream erosion and 55% of in-stream deposition were generated by the streambanks. Note that Fig. 6 only shows the net depositions. Net sediment deposited to the streambanks over the study period was 37 tons and 18 tons in W_W and W_E, respectively (Fig. 6). Sediment deposition was the dominant mechanism in right banks. Left banks usually were stable, but few reaches, i.e. S_{W5}–S_{W6}, S_{E2}–S_{E3}, S_{E3}–S_{E4} had net erosion on their left banks. Note that these reaches still had net sediment deposition on streambanks overall because of the high sediment deposition on their right banks. Close inspection of Figs. 3 and 4 shows that the net erosion of left banks actually happened only at sites S_{W6} and S_{E3}. Except the left bank of these two sites, SMZs in the study watersheds functioned well to stabilize streambanks by hindering in-stream bank erosion.

Channel dimensions

Both study streams were located in the same physiographic province, both were surrounded by forest, and both were under the impacts of upstream disturbances, however, they have different stream classification based on Rosgen (1994) (Table 4). West stream was classified as stream type E with low width to depth ratio (Rosgen 1994) while East stream was classified as type F with very high width to depth ratio (Rosgen 1994). Brantley et al. (2013) collected stream morphology data at 21 reference streams in Piedmont Alabama, and found that they were classified as Rosgen stream types B, C or E. When the parameters of Rosgen stream classification of the study streams (bankfull cross-sectional area, bankfull width, bankfull mean depth and slope) were

Table 3 Estimated sediment transport from 3/31/2014 to 7/26/2015

Streams	Survey sites	Sediment yield at outlet (m^3)	Net sediment deposition at S_1–S_6 (m^3)	Net sediment input to S_1–S_6 (m^3)	Channel surface area (m^2)	Average aggradation (mm)
West	S_{W1}–S_{W6}	12.5	68.8	81.3	3459	24
East	S_{E1}–S_{E6}	61.5	16.6	78.2	3101	10

Sediment input (m^3) = sediment yield at outlet (m^3) + Net sediment deposition (m^3), aggradation (mm) = [net sediment deposition (m^3)/channel surface area (m^2)] × 1000

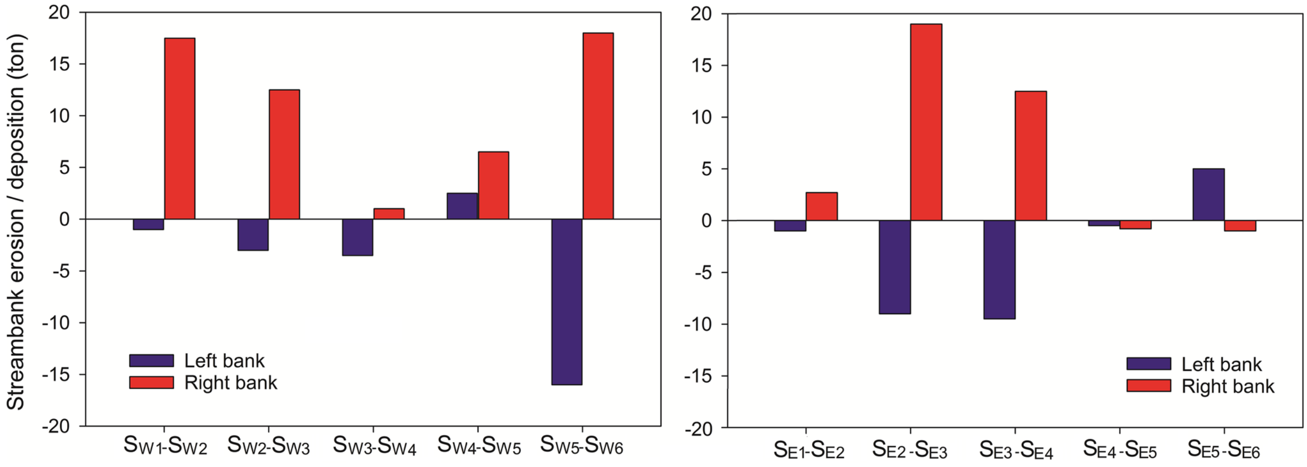

Fig. 6 Estimated net streambank erosion/sediment deposition over the study period between the survey sites of West and East streams

Table 4 Summary of West and East streams for Rosgen Stream Classification (1994)

Parameters	West Stream	East Stream	Parameters	West Stream	East Stream
Bankfull area (m^2)	0.7–1.5	0.6–1.02	Drainage area (ha)	37	50
Bankfull mean depth (m)	0.3–0.6	0.2–0.4	Sinuosity	1.6	1.3
Width to mean depth ratio (m/m)	9.0–11.5	12.0–17.1	Water surface slope (m/m)	0.019	0.014
Flood-prone width (m)	13.4–24.4	4.3–5.2	BHR	1–1.2	1.9–4
Entrenchment ratio (m/m)	3.6–7.4	1.2–1.6	Rosgen classification	E5	F4

compared with the parameters of these reference streams, we found that West stream is similar to the reference streams of Brantley et al. (2013). However, there was no type F stream among the 21 Alabama piedmont reference streams studied by Brantley et al. (2013). In addition, although similar bed material was expected from both streams due to the disturbance effects, pebble count data showed that study streams had different bed material. The median particle size (D_{50}) was 0.7 mm for the West stream while it was 11.5 mm for the East stream. Bed material of the West and East streams were coarse sand and medium gravel, respectively. Although channel cross sections exhibited very dynamic patterns changing frequently over short time periods in response to the upstream urban disturbances (see Figs. 3, 4), these disturbances did not lead to any changes in Rosgen stream classification. According to Brantley et al. (2013), land disturbances usually cannot affect stream classification in such short time periods. Another reason for the unchanged stream classification following the upstream urban disturbance may be the existence of the SMZs along the study streams and their role in stream stabilization.

Discussion

In-stream erosion and deposition

As stated above, cross sections exhibited very dynamic patterns in both watersheds. The magnitude of a rainfall event is likely the biggest factor modifying the morphology of stream cross sections. For example, the rain events on 5/5/2015 and 7/26/2015 had different effect on channel bottom morphology at S_{E5} (Fig. 4). Prior to the first event (i.e., 5/5/2015), relatively higher amount of precipitation likely resulted in higher deposition, and consequently a bulge, in the middle of the stream, while milder events following this event transported this deposited sediment. The observed in-stream erosion and deposition during the study period suggest that both streams have been affected by the alterations in upland runoff and sediment supply, which resulted in changes in morphology of cross sections. LU/LC disturbances within a watershed can have a dramatic effect on water and sediment discharge (Boix-Fayos et al. 2007; Cavus et al. 2017), and cause higher peak flows by creating an imbalance of forces in the channel (Schumm 2003). An increase/decrease in the amount of sediment delivered from upstream areas may result in sediment deposition/erosion in downstream channels, thus leading to changes in morphology of stream cross sections (Schoonover 2005; Nelson et al. 2006).

The amount of sediment deposited in the West stream channel was higher than the amount of sediment deposited in the East stream channel (see Table 2). Surprisingly, the amount of sediment eroded from the West stream channel was higher than the amount of sediment eroded from the East stream channel too (see Table 2). This was likely because more sediment entered and transported in the West stream channel from the disturbed area. The difference between water velocities may also explain the higher in-stream deposition in West stream channel. Flow in the East stream was always faster than the flow in the West stream throughout the study period because of its narrower channel. Sediment transport capacity is known to drop with reduced stream velocity. Hence, sediment particles likely started depositing to the streambed much earlier and in a greater amount in the West stream than the East stream. Slope variations through the stream channels may have also played an important role in the increases/decreases on deposition and erosion in the stream channels. For example, at the West stream channel, the slope between S_{W3} and S_{W4} is very high compared to the slopes of the other reaches (Table 1), and the lowest deposition was observed between S_{W3} and S_{W4} (Table 2). The slope and in-stream deposition between the remaining survey sites did not change significantly at the West stream channel. The average slope is lower at the upstream reaches of the East stream (except S_{E1}–S_{E2}), and it increased through downstream (Table 1), presenting a convex shape. This may have contributed to in-stream deposition between upstream survey sites, and erosion between downstream survey sites.

Although the West stream channel was exposed to higher sediment input and higher net sediment deposition, lower sediment yield was observed in the West stream channel compared to the East stream channel during the study period. In addition to the discussions above, higher net sediment deposition in the West stream channel can also be associated with the pattern in sediment load downstream. Cavus et al. (2017) stated that sediment load decreased from upstream to downstream in W_W but was more consistent through downstream in W_E. This also supports our finding that most of the sediment entering to West stream was deposited over the study period. Observed morphological changes of cross sections at the survey sites are clearly caused by the unusually high amount of sediment entering the study streams from the disturbed areas. This may suggest that the capacity of improperly installed and maintained straw bales and silt fences located around the upstream disturbances were poorly designed and mostly inefficient. Straw bales and silt fences are adopted for use in construction sites for erosion and sediment control, but many applications of straw bales are not successful for erosion and sediment control due to nature of straw bales, problems with placement, maintenance and installation (Fifeld 1999). For instance, Wishovski et al. (1998) evaluated the trapping efficiency of silt fences and found that decreasing particle size of sediment reduces the efficiency of trapping.

Streambank erosion/deposition

Streambank erosion and deposition are very significant contributors to stream instability. The majority of suspended sediment is usually generated by bank erosion in the stream channel (Trimble 1997). Presence of SMZs along the streams can clearly affect this as observed in this study. The streambanks downstream of the urban disturbance areas in both watersheds almost had no net erosion. Both streams were surrounded by well-maintained SMZs.

Net sediment deposition contributed from streambanks to the sediment input over the study period was higher in the West watershed. Palmer et al. (2014) found that total sediment contribution from streambanks between 2005 and 2011 was 33% of the total sediment load in Walnut Creek watershed in Iowa, which was predominantly covered by agricultural land. Sediment generated by streambanks in two agricultural watersheds within central claypan areas was 79–96% of the total in-stream sediment (Willett et al. 2012). Although our sediment input was fairly high in both streams over the study period, streambanks contributed low amount of sediment to the streams. This suggests that SMZs in each watershed were sufficient to stabilize streambanks by hindering in-stream bank erosion. Composition of riparian vegetation contributes to the susceptibility of streambank erosion. SMZs serve as a filter and stabilizer for streambanks (Naiman and Decamps 1997). SMZs along the stream channels with woody species are effective in providing streambanks stability. This again pointed out that the main source of sediment to the streams was the intensive disturbances performed in the upstream sections of the study area.

Channel dimensions

As we observed in this study, several studies conducted in the Piedmont region of the US and the southern/southeastern US have documented the effects of watershed disturbances on channel morphology (Doll et al. 2002; Nelson et al. 2006; Elmore and Kaushal 2008). Leopold et al. (2005) and Hardison et al. (2009) both observed an increase in bed aggradation and a decrease in channel depth due to urbanization in Rockville, MD Piedmont and in NC along Coastal Plain streams, respectively. In another study, Allmendinger et al. (2007) found that land disturbances provided approximately 40% of watershed sediment yield to a stream in Montgomery County, MD. Similarly, Keen-Zebert (2007) observed a decrease in channel depth in response to urbanization in Fayetteville, AR. As stated above, upstream urban disturbances resulted in cross-sectional changes due to instream erosion and deposition in our study, however, these disturbances did not cause any changes in stream classifications of the study streams. Compared to previous studies above, we believe that predicted aggradation depths for both streams in our study were not substantial to lead to any changes in the parameters of Rosgen stream classification, such as entrenchment ratio, width to depth ratio and bankfull width/depth. The main reason for the stability of the stream classification parameters following the upstream urban disturbances may be the existence of the SMZs along the study streams. Previous researches substantiate our findings (Naiman and Decamps 1997; Nakamura and Swanson 1993; Lakel 2008). In a similar study, Naiman and Decamps (1997) stated that vegetation within stream buffers mitigate the impacts of heavy flow on channel geometry by holding the materials in place by their roots, and slowing water velocity by their stems. In another study, Nakamura and Swanson (1993) observed the influence of riparian vegetation on channel geometry, and pointed out that trees and large coarse woody debris within stream buffer zones can prevent channel widening and steeping. Although the poorly designed BMPs (i.e., silt fences and straw bales) installed near the disturbed area seemed insufficient to balance the variations in sediment supply under the impacts of upstream disturbances, the SMZs present downstream were found to be sufficient to stabilize streambanks.

Our data suggest that the difference in channel dimensions of East stream compared to West stream was not caused by the current disturbance effect. Although channel morphologies of stream cross sections have changed frequently during this 18-month period, commonly used parameters of Rosgen stream classification remained stable. It is possible to detect erosion and deposition in stable streams over short periods, but there is usually no change in stream classification over short periods (Hey 1997). We observed aggradation in both stream channels as a result of upstream disturbances, but it was likely not sufficient to significantly change the stream classification of the study streams. If upstream disturbances were to lead changes in stream classification, both streams would have been affected. The difference in parameters of Rosgen stream classification of the East stream is likely associated with the legacy effects of sediment from historical land use disturbances in southeast of USA. Streams of southeastern Piedmont have been exposed to excess sediment during and end of the 1800s by poor agricultural practices (Markewitz 2007). East stream may still be in the process of transporting legacy sediments as a result of land use disturbances while West stream may have reached a stable equilibrium condition.

Brantley et al. (2013) found that most of the 21 reference streams in Alabama Piedmont had gravel bed material. The difference of bed material between West and East stream may be attributed to the water velocities. The higher water velocities in East stream may have carried finer bed material to downstream, and coarser material may have remained in the stream bed. In addition, disturbances may also have been more severe in W_W as it was observed that S_{W1} had approximately 50% higher sediment concentration than S_{E1}. Another consideration may be the sequence of the disturbance. Construction usually brings sandy texture sediment to the streams. Thus, since upstream disturbances first started in W_E, sandy sediment in East stream may have been washed out over time and coarser sediment may have remained in the streambed of the East stream. Sandy sediment in West streambed may have not been carried out yet due to the later start of upstream disturbances in W_W.

Conclusions

Use of BMPs to mitigate the impacts of human induced disturbances on streams has been studied for many years. Because of external influences, streams may be subject to higher temperatures, sediment loading, and streambank erosion if BMPs are not present. However, the efficacy of BMPs in maintaining stream morphology in watersheds exposed to intensive land disturbances may be reduced. This study suggest that intensive headwater disturbances may negatively influence downstream morphology of stream cross sections in short term where SMZs are in place, if no BMPs are present or existing BMPs near the upstream disturbances are poorly functioning. In such cases, the effectiveness of downstream BMPs may potentially be questioned by landowners and/or forest managers. However, our findings indicated that the impacts of the upstream disturbances likely would have been worse if there were no downstream BMPs (i.e., SMZs), because the downstream SMZs were found to be sufficient to stabilize streambanks. Therefore, this study points out the necessity of proper BMP implementation over the entire watershed, especially at disturbance sites. This study further emphasizes the importance of watershed management in a holistic fashion to mitigate the impacts of disturbances more efficiently. Future studies are encouraged to evaluate the recovery of watershed systems following the completion of the disturbances.

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