Journal of Environmental Management 185 (2017) 60–69

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Sediment source identification and load prediction in a mixed-use Piedmont watershed, South Carolina

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ARTICLE INFO

Article history:
Received 5 May 2016
Received in revised form
17 October 2016
Accepted 18 October 2016
Available online 28 October 2016

Keywords:
Suspended sediment
Sediment fingerprinting
Bank erosion
Piedmont
Stable isotopes

ABSTRACT

Many streams in the Piedmont region of the southeastern United States transport a disproportionately large amount of suspended sediment in response to moderately increased streamflows. Transport and deposition of excess sediment affect the stability of the channel and the health of the biological community; therefore, identifying the main source(s) of sediment and assessing the relationships between source, transport, and streamflow are critical to aquatic life and habitat management, dynamic equilibrium preservation, and development of feasible mitigation scenarios. The objectives of this study were to: (1) predict the annual suspended sediment yield and (2) identify significant contributing upland sources of sediment in the Lawsons Fork Creek basin, a 217 km^2 mixed-use watershed in the South Carolina Piedmont. A regularly monitored cross-section located in the downstream reach was equipped with a passive sediment sampler, gage-height recorder, and sediment tiles. Streamflow and sediment concentration were measured over a 24-month period under variable hydrologic regimes. Results indicated that the average annual sediment yield (168 $t/km^2/yr$) is significantly higher than yields documented in Piedmont watersheds of comparable size. To identify and prioritize sources of sediment contribution, stable isotopes of nitrogen ($\delta^{15}N$) and carbon ($\delta^{13}C$) were used as tracers. Source material was compared with suspended sediment near the watershed outlet (target material) and SIAR, a Bayesian Inference model, was used to estimate source apportionment. Results of this source study indicate that approximately 60% of the total sediment load in the water column during high flow events is derived from stream bank erosion. Findings are consistent with observed unstable stream bank conditions in the watershed. This study supports the use of a dual-isotopic fingerprinting approach in tandem with traditional sediment monitoring as a cost-effective method to identify and target sediment sources in a mixed-use watershed.

1. Introduction

Sediment and its movement to, through, and from streams is the most pervasive and costly form of water pollution in North America (Pimentel et al., 1995). Currently, nearly 20% of U.S. streams do not meet water quality standards set forth by individual states owing to high sediment levels and sediment loading from non-point sources (USEPA, 2006). Typical non-point sources of sediment from upland areas include runoff from agricultural lands, pastures, urban areas/construction sites, and forested lands, while stream banks and the streambed are considered in-channel sources. Identifying the source(s) of excess sediment in a watershed is crucial to support management programs that attempt to address well-known harmful effects sediment has on aquatic life, the biological community, and the overall health of the fluvial system.

Sediment source tracing is an effective first step in controlling excess sediment contribution to a watershed because it offers a specific area to target mitigation efforts (Dutton et al., 2013). Since the mid-1970's, sediment fingerprinting, a form of source tracing, has been used in watershed studies to establish the origin and character of eroded source(s) of suspended sediment in small (<100 km^2) to medium sized (<250 km^2) river basins. The fingerprinting approach compares select physical and/or geochemical characteristics of potential upland sediment sources in a watershed with those sampled in the water column. By cross-referencing the fingerprint of the upstream source samples with the suspended sediment samples, the potential provenance of the sediment in transport can be determined. This approach provides a direct method for quantifying watershed sources of fine-grained suspended sediment (Collins et al., 1997a, 1997b; Gellis et al., 2009;

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http://dx.doi.org/10.1016/j.jenvman.2016.10.036
0301-4797/

Gellis and Walling, 2011; Motha et al., 2003; Mukundan et al., 2012; Walling and Woodward, 1995). Physical and geochemical properties commonly used to distinguish upland sources include: sediment color (Grimshaw and Lewin, 1980); mineralogy (Motha et al., 2003); magnetic properties (Slattery et al., 2000); trace elements (Collins et al., 1998); fallout radionuclides (Walling and Woodward, 1992; Wallbrink and Murray, 1993; Wallbrink et al., 1999; He and Owens, 1995); and stable isotopes (Fox and Papanicolaou, 2007; Gellis et al., 2009; Fox et al., 2010; Mukundan et al., 2010a, 2010b). While different tracers and tracer combinations have been tested in various parts of the world, Walling (2013) points out that selecting specific tracers to provide adequate and confident source ascription is challenging because there are few guidelines in the literature.

Sediment source tracing is often carried out in tandem with a traditional sediment monitoring program (Minella et al., 2008) to help determine the relationship between the material eroded in the uplands and the material transported in the water column (Walling, 1983). This relationship is difficult to quantify because sediment discharge is not directly proportional to sediment erosion. Sediment flux is influenced by both natural processes and anthropogenic changes in the watershed and is typically considered a moving target. Therefore, both sediment source and sediment yield should be examined simultaneously where the goal is to identify, target, and address management concerns arising from excess sedimentation.

The objectives of this study were: (1) to predict annual suspended sediment discharge (tons/year ((t/yr)) using traditional field measurement and regression techniques and (2) to identify significant contributing upland sources of sediment using stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). The Lawsons Fork Creek watershed of South Carolina was selected for this study owing to: (1) expanding urbanization in the nearby city of Spartanburg, (2) higher than expected sediment loads predicted by preliminary modeling, and (3) widespread channel aggradation and bank failure in the watershed. The unstable condition of stream banks in many areas throughout the watershed prompted an initial hypothesis that the majority of sediment transported in the Lawsons Fork Creek under high flow conditions was derived from eroded bank material.

2. Study area

The Lawsons Fork Creek watershed is located in the Broad River Basin in the Piedmont region of the southeastern United States (Fig. 1a). The Broad River has headwaters in the Blue Ridge Mountains of North Carolina and terminates at the confluence with the Saluda River to form the Congaree River just below the fall line near Columbia, South Carolina. The Lawsons Fork Creek watershed is a 217 km^2 mixed-use watershed with a total of 142.7 stream kilometers, a maximum elevation of 357 m, and an elevation of 161 m at the mouth. The watershed receives approximately 130 cm of precipitation annually and has a mean annual temperature of 15.5 °C. Snowfall is minimal with an average of 3.6 cm per year. The stream flows through the city of Spartanburg in Spartanburg County, which has a population of approximately 300,000. The population has increased by nearly 70% in the last four decades and the county has been designated as a high-growth potential area (SCDHEC, 2007). The study basin is 43% developed, 33% forest, 16% pasture, 4% grassland and 1% fresh water (Fig. 1b).

3. Materials and methods

3.1. Streamflow and suspended sediment measurement

A regularly monitored cross-section near the mouth of Lawsons Fork Creek was visited approximately every two weeks over a period of 24 months. Depending on flow conditions at the time of sampling, cross-sectional water velocity was measured either by using a hand-held Marsh- McBirney Flo-Mate™ or by lowering a USGS Type AA current meter and 15 lb. sounding weight attached to a reel and cable assembly from a highway bridge above the cross-section. Additionally, a HOBO U-20® data logger was anchored to the stream bank at half the average water depth and 5869 water pressure measurements (kPA) were converted into daily streamflow data through ordinary least squares regression of measured streamflow and recorded pressure ($R^2 = 0.91$). This yielded a dataset of 479 daily streamflow measurements.

Sixty-four flow-weighted depth-integrated suspended sediment samples were collected across multiple verticals employing the equal-width increment (EWI) method (Edwards and Glysson, 1999; Guy and Norman, 1970; Nolan et al., 2005). These sediment data were used to establish a relationship between suspended sediment concentration (mg/L) and water discharge (cubic meters per second (cms)). A USGS hand-held DH-48 sampler was used when sampling in low flow conditions; a USGS D-74AL sampler was suspended from the bridge above the cross-section to collect samples during high flow conditions.

Water samples collected from the cross-section were composited in the laboratory and mass concentration (mg/L) was determined by filtering the sample through a 1.0 μm 47 mm glass-fiber filter (GFF) and drying the filter at 105 °C prior to weighing it (Guy, 1969). The concentration of suspended sediment (mass/volume) was then converted to suspended sediment flux (mass/time) using observed stream discharge (volume/time).

Annual sediment flux (t/yr) and stream discharge were estimated using the adjusted maximum likelihood estimation (AMLE) method within the model LOADEST (Runkel et al., 2004; Cohn, 2005). LOADEST employs statistical regression techniques based on the rating-curve method (Horowitz, 2003) and uses the following quadratic equation to examine the relation between suspended sediment discharge and streamflow:

$$\ln(L) = a_0 + a_1 \ln(Q) + a_2 \ln(Q_2) \quad (1)$$

where L is the suspended sediment load; ln(Q) is the stream discharge normalized to mean value; and a_0, a_1 and a_2 are regression coefficients.

3.2. Sediment sample collection for source tracing

3.2.1. Isotopic tracers

Sediment fingerprinting is an effective tool to help determine sediment source type as well as spatial origin (Gellis and Walling, 2011). Mukundan et al. (2012) have indicated that sediment source fingerprinting is undergoing transformation from a research tool to a management tool, while Mckinley et al. (2013) have proposed a streamlined approach that could help regulatory agencies apply sediment fingerprinting techniques as a routine part of sediment-related (i.e., TMDL) field studies. In the Piedmont region, sediment tracing studies using stable isotopes of nitrogen and carbon to track sediment sources were successfully carried out by Mukundan et al. (2010a, b) and expanded on by Mckinley et al. (2013). Their study area was located approximately 130 km west of the current study area and they indicated that their methods and results were likely applicable to similar watersheds in the region. Therefore, we applied a similar composite fingerprint of stable isotopes ($\delta^{15}N$ and $\delta^{13}C$) to assign importance to significant sediment sources in the Lawsons Fork Creek watershed, while increasing exposure and strengthening validation of this approach for use in other Piedmont streams experiencing sediment-related issues.