

# Modeling hillslope sediment yield using rainfall simulator field experiments and partial least squares regression: Cahaba River watershed, Alabama (USA)

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**Abstract** Hillslope erosion processes such as rainsplash erosion and slopewash are a major source of fine sediment that causes water-quality problems in many river systems. Hillslope sediment yield is controlled by both climatic and watershed characteristics. Understanding the relative sensitivity of sediment yield to soil and watershed characteristics under different precipitation intensities is important for identifying hotspots of sediment yield and the likely response of sediment yield to changing climate and land use. Here, field experiments on sediment yield were conducted in Alabama's (United States) Cahaba River watershed under varying precipitation intensities using a rainfall simulator. Using data on soil and watershed characteristics, partial least squares (PLS) regression models were developed of sediment yield under both "more intense" (recurrence interval  $\approx 10$  years) and "less intense" (recurrence interval  $\approx 1$  year) simulated rainfall events. The resulting models were used to create spatially explicit estimates of sediment yield under different precipitation intensities for the Cahaba River watershed. The optimized PLS models had a cumulative  $R^2$  of 0.41 and 0.73 for the "more intense" and "less intense" rainfall events, respectively. The higher  $R^2$  of the "less intense" model is attributed to higher significance of the heterogeneity of watershed variables under less intense precipitation. Significant variables that were retained in both models included percent sand, percent clay, percent organic matter, and slope. The results support the use of PLS modeling to analyze the results of field experiments using rainfall

simulators to examine both climatic and watershed controls on hillslope sediment yield.

**Keywords** Precipitation intensity · Rainsplash erosion · Soil characteristics · Spatial modeling

## Introduction

Erosion and sediment transport processes are major drivers of the physical, chemical, and ecological quality of river systems. Rivers are supplied with sediment from adjacent hillslopes throughout the watershed. Interrill erosion is the mobilization of soil particles that have been subject to rainsplash erosion and shallow overland flow and represents one of the major means by which soil is removed from hillslopes (Gilley et al. 1985). The direct rainsplash impacts have been shown to be responsible for the majority of sediment transport on bare slopes (An et al. 2012). Excessive soil erosion represents a significant environmental problem with both on-site and off-site impacts (e.g., Grauso et al. 2010; Rozos et al. 2013). These impacts can potentially include natural hazards such as flooding and landslides (Bathrellos et al. 2012; Chousianitis et al. 2016).

Sediment yield is a function of several climatic and watershed variables at multiple spatial scales. The climatic variables consist of factors that are external to the watershed itself, notably precipitation intensity. Although precipitation intensity can exhibit significant variability within a small area, this spatial heterogeneity is controlled predominantly by characteristics of the storm rather than the watershed. With increasing precipitation intensity, the erosive potential of rainfall would be expected to increase. More intense precipitation results in a greater rate of rainsplash erosion, which allows for soil grains to be

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transported by surface runoff (Nearing 2001; Wan et al. 2014). Variations in precipitation intensity over the course of an individual storm event also affect the total runoff and sediment load generated (An et al. 2014). In addition to its impact on rainsplash erosion, more intense precipitation is also associated with higher overland flow velocities (Froehlich 2011). Highly intense precipitation has been found to reduce surface roughness relative to less intense rainfall, because of rainsplash erosion leading to eluviation and resulting size segregation (Chappell et al. 2007). At a seasonal scale, total precipitation amount also plays an important role in sediment yield. Although more rainfall results in more erosive energy in the form of rainsplash and overland flow, higher rainfall is also associated with denser vegetation in moisture-limited environments (Scharrón 2010).

In addition to the climatic drivers, characteristics of the watershed itself also affect sediment yield. These characteristics vary within a watershed at multiple spatial scales. At the broadest scale, different physiographic regions are characterized by differences in bedrock geology and topography, which provide a first-order control on soil depth and chemistry. Within physiographic regions, physical properties of the soil determine how quickly incoming precipitation can enter and percolate through the soil column, as well as the energy needed to detach and transport particles (Doerr et al. 2000). These properties are affected by factors such as soil texture, organic matter content, degree of compaction, and the nature of vegetation. At the finest spatial scale, site-level topographic factors such as slope angle and aspect control local patterns of erosion and deposition (Lee et al. 2013). Although steeper slope angles are generally associated with higher erosion rates, there may be thresholds at which increases in slope are no longer associated with increased sediment yield (She et al. 2014). Anthropogenic factors, such as land-use/land-cover change (LULCC), also influence soil properties through addition or removal of vegetation, compaction, creation of impermeable surfaces, and alteration of hydrologic processes (Wu et al. 2013). Because rates of rainsplash erosion and slopewash are dependent on these watershed characteristics that vary at multiple scales, it is difficult to generalize sediment yield resulting from a given precipitation intensity. Instead, relationships between soil characteristics and sediment yield can be empirically estimated for a given watershed based on field observations and experiments (e.g., Seeger 2007; Chanson et al. 2008; Zhang et al. 2014). A systematic assessment of the controls on sediment yield that are most relevant at different spatial scales can usefully contribute to generalization of understanding of the sources of fine sediment.

While the relative significance of different climatic and watershed controls on sediment yield is variable, an

additional problem is that these variables may interact with one another in complex ways. For example, the relationship between precipitation intensity and sediment yield is likely to vary among different soil types, land covers, and topographic settings. Soil features such as biological soil crusts can either increase runoff or stabilize soil surfaces, and the net effect of such features on sediment yield may vary under different precipitation intensities (Rodríguez-Caballero et al. 2013). Although forest vegetation reduces runoff and sediment yield, its effectiveness in these reductions is lower for highly intense precipitation (Li et al. 2012; Zhang et al. 2014). The relationship between increasing slope angle and increasing sediment yield may not apply to the highest-intensity rainfall events (Kang et al. 2001). Soil amendments designed to reduce runoff and soil loss differ in their effectiveness depending on the intensity of the rainfall and the angle of the slope (Pan and Shangguan 2006; Gholami et al. 2013). Moreover, many of the driving climatic and watershed variables are not stable in time. At the event scale, the antecedent particle-size distribution can either enhance or impede erosion so that the mass of sediment eroded from identical rainfall events may vary widely unless initial conditions are also identical (Kim and Ivanaov 2014). Soil surface roughness, and therefore runoff and sediment yield, can change over the course of a storm in response to intense precipitation (Zheng et al. 2014). Longer-term climate variability and change may lead to changes in both precipitation amount and intensity. LULCC is associated with changes in land-surface conditions that exert a major control on hillslope sediment transport (Boix-Fayos et al. 2008; Durán Zuazo et al. 2012). The interaction among climate and watershed characteristics, and their potential variability over time, is an important area for study.

One classical method for estimating hillslope sediment yield is the Universal Soil Loss Equation (USLE), which is based on a simple linear combination of rainfall erosivity, soil erodibility, slope angle and length, cover type, and erosion-control practices (Wischmeier and Smith 1978). In addition to soil-loss methods such as USLE, sediment delivery techniques have also been developed that account for ponding and deposition on hillslopes and estimate the sediment yield actually transported to rivers (e.g., Svoray and Ben-Said 2010). However, few studies have constructed spatially explicit models of potential sediment yield that integrate climatic factors and watershed characteristics at an event scale.

Sediment yield has been empirically measured using a variety of methods, including coring of reservoir (e.g., Griffiths et al. 2006) and lake sediments (Liermann et al. 2012), measurement of sedimentation behind check-dams (Molina et al. 2008), and long-term field monitoring (Nadal-Romero et al. 2008; Nu-Fang et al. 2011). In

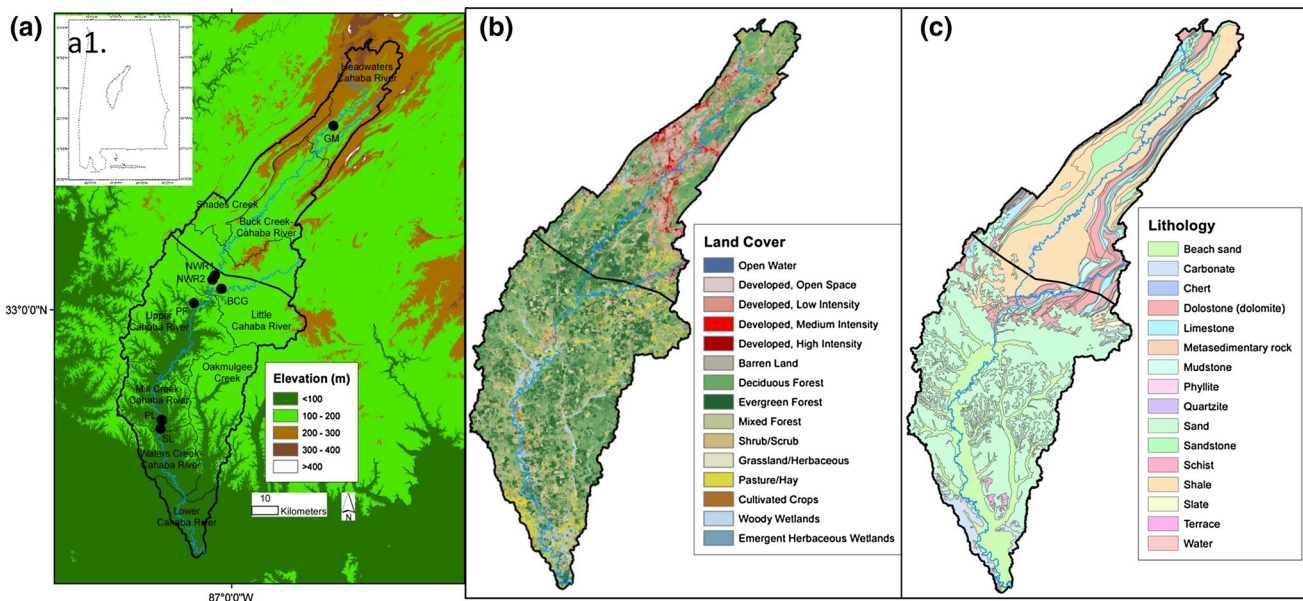
addition to techniques that focus on the sediment yield actually delivered to rivers and lakes from the surrounding watershed, soil loss from a plot can be directly measured with Gerlach troughs and other types of runoff and sediment traps. In order to control for precipitation intensity, rainfall simulators are commonly used in laboratory settings (e.g., Akbarzadeh et al. 2009). Portable rainfall simulators have also been used to conduct field experiments at natural sites (e.g., Pierson et al. 2001, 2009; Paige et al. 2002; Holifield Collins et al. 2015). Such field experiments typically use parametric statistics such as correlation coefficients and ordinary least squares regression to quantify relationships between predictor and response variables (e.g., Martínez-Zavala et al. 2008; Jordán and Martínez-Zavala 2008). Partial least squares (PLS) regression techniques have been used to model environmental variables such as nitrate concentrations in soils (Chighladze et al. 2012) and soil organic matter content (Lamsal 2009; Conforti et al. 2013), but mostly for laboratory or remote-sensing data. The contribution of the present study is to bring together field-based rainfall simulator experiments with the statistical technique of PLS regression.

The aim of this paper is to explore the relative significance of different watershed controls on hillslope sediment yield under different precipitation intensities. Specifically, this project analyzed the relationships among precipitation intensity, soil characteristics, and sediment yield in the Cahaba River watershed. The Cahaba River is the longest undammed river in Alabama (USA) and a hotspot of aquatic biodiversity, but is currently listed under the Clean Water Act for excessive sedimentation problems. This

empirical approach used data on soil characteristics obtained through fieldwork and laboratory analysis and data on sediment yield derived from field experiments with a rainfall simulator. The field data, along with existing geospatial datasets on watershed characteristics, were used to construct spatially explicit PLS event-based regression models of sediment yield under varying precipitation intensities for the Cahaba River watershed. The approach is novel in that it combined field experiments with PLS regression in order to develop spatially explicit empirical models of potential sediment yield at an event scale. The paper presents a potentially useful novel technique for estimating hillslope sediment yield.

### Study area

The study area for this research was the Cahaba River watershed in central Alabama, USA (Fig. 1). The Cahaba River is a major tributary of the Alabama River, with a drainage area of approximately 4843 km<sup>2</sup>. The upper portion of the Cahaba River is located in the Valley and Ridge physiographic region, and the lower part is on the Gulf Coastal Plain (El-Kaddah and Carey 2004). The Valley and Ridge region is characterized by deeply folded and thrust-faulted layers of Cambrian to Pennsylvanian (540–290 mya) sedimentary rocks, with ridges composed primarily of Pottsville Formation sandstone and valleys cut through shale, limestone, and dolomite (Kidd and Shannon 1978). The Gulf Coastal Plain is characterized by Mesozoic to recent (<140 mya) sedimentary rocks, including chalk,



**Fig. 1** Maps of **a** the Cahaba River watershed field sites (with site codes defined in Table 2) and sub-watersheds; **(a1)** the location of the Cahaba River watershed within the state of Alabama; **b** land cover; and **c** lithology

sandstone, limestone, and claystone, as well as by extensive alluvial deposits (Jones 1967). These physiographic provinces extend well beyond Alabama and can therefore be considered representative of a broader region of the southeastern USA. Both the Valley and Ridge and Gulf Coastal Plain portions of the Cahaba River watershed are areas in which rates of rainsplash erosion are comparatively high, because of steep slopes in the Valley and Ridge region and large quantities of unconsolidated sediment on the Gulf Coastal Plain. Also, both regions are characterized by highly intense precipitation because of the humid subtropical climate with frequent convective activity in the summer and frontal storms in the spring, with approximately 5 % of average annual precipitation arriving in the driest month (October) and 11 % in the wettest month (March) (SERCC 2016). Average annual rainfall is approximately 1428 mm in the upper Valley and Ridge region of the watershed and 1374 mm on the Gulf Coastal Plain (PRISM Climate Group 2016). Typical soils of the Valley and Ridge portion of the watershed are deep, well-drained, moderately permeable soils formed in loamy residuum from sandstone or shale, from the Townley-Nauvoo-Montevallo group. The Gulf Coastal Plain portion of the watershed is characterized by very deep, well-drained, moderately permeable soils that formed in loamy alluvium on floodplains, from the Riverview-Minton-Leeper-Canton Bend-Cahaba-Annemaine group (USDA 2016). The rainfall and runoff erosivity R factor in the Universal Soil Loss Equation for Alabama ranges from approximately 300–350, among the highest values in the USA (Wischmeier and Smith 1978). The majority of the watershed area is dominated by managed evergreen (21 % of the total watershed area), deciduous oak-hickory (28 %), and mixed cypress-tupelo bottomland and swamp forests on floodplains (9 %), with extensive urban areas in the upper watershed (11 %) and some agriculture (11 %) in the lower watershed (Schotz 2016). The upper reaches of the Cahaba River are listed under Section 303(d) of the Clean Water Act for nutrients and siltation, primarily as a result of urban development in the headwaters of the river in the Birmingham metropolitan area (ADEM 2013). These existing sedimentation problems in an otherwise

ecologically functional river (which supports a wide variety of aquatic species, including several endangered and threatened species) make the Cahaba watershed a priority target for conservation and restoration. Additionally, the watershed's bifurcation by two physiographic provinces, which are similar to other regions of the southeastern USA, makes the Cahaba River watershed a highly suitable study site for the analysis of soil and watershed controls on sediment yield under varying precipitation intensities.

## Methods

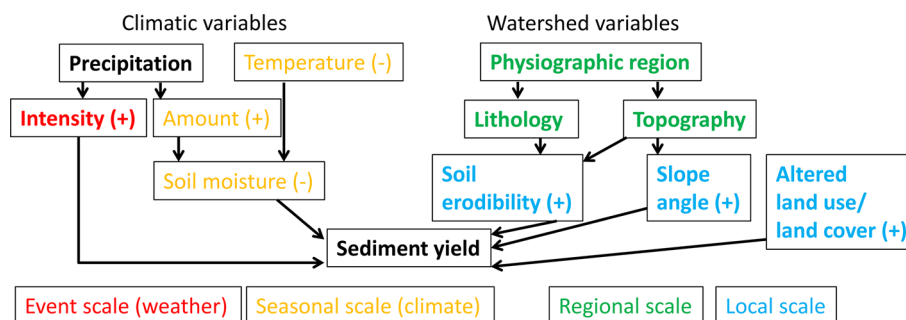
### Conceptual framework

The conceptual framework for this project was based on a set of climatic and watershed variables that jointly determine hillslope sediment yield (Fig. 2). The climatic variables are relevant at different temporal scales (precipitation intensity at the event scale and soil moisture at the seasonal scale), and the watershed variables are relevant at different spatial scales (physiography at the regional scale and soil erodibility, slope angle, and alteration of land use/land cover at the local scale). The objective of this project was to examine which watershed variables are most significant in influencing hillslope sediment yield under different precipitation intensities, using a combination of fieldwork, laboratory analysis, and statistical and geospatial modeling.

### Fieldwork methods

Seven field sites were designated within the Cahaba River watershed, and fieldwork was carried out in June and July 2015 (Table 1). The sites were chosen partly on the basis of access (most of the watershed area is privately owned) and partly to represent the watershed's range of physiographic, lithologic, and land-cover characteristics. One site was in the Valley and Ridge physiographic province in the upper watershed, two sites in the Gulf Coastal Plain in the lower watershed, and four sites along the Fall Line, which is transitional between the two physiographic regions (Fig. 1). At each of the seven sites, a transect (mean

**Fig. 2** Conceptual diagram of the climatic (from seasonal- to event-scale) and watershed (from regional- to local-scale) controls on hillslope sediment yield. The *bolded items* are those that are explicitly considered in this paper





**Table 1** Characteristics of field sites

Site name	Latitude (°N)	Longitude (°W)	Elevation (m)	Mean annual precipitation (mm)	Soil series
Grants Mill Road	33.51	86.65	150	1413	Townley-Nauvoo-Montevallo
National Wildlife Refuge 1	33.08	87.06	87	1435	Townley-Nauvoo-Montevallo
National Wildlife Refuge 2	33.10	87.06	89	1444	Townley-Nauvoo-Montevallo
Bibb County Glades	33.06	87.03	80	1427	Townley-Nauvoo-Montevallo
Pratt’s Ferry	33.09	87.13	104	1420	Townley-Nauvoo-Montevallo
Perry Lakes	32.69	87.24	44	1367	Riverview-Minton-Leeper-Canton Bend-Cahaba-Annemaine
Sprott Landing	33.02	87.13	42	1420	Riverview-Minton-Leeper-Canton Bend-Cahaba-Annemaine

length = 139 m, standard deviation = 30 m, range = 210 m) was established from the river bank to the drainage divide, with three sampling locations along each transect at which rainfall simulator field experiments were conducted and soil samples were taken. The result was a total of 21 sampling locations divided evenly among bank, mid-slope, and ridgetop locations.

At each sampling location, a series of field experiments was performed with Gerlach troughs and a rainfall simulator in order to estimate sediment yields under a range of precipitation intensities. A Gerlach trough is an instrument that captures surface runoff and its associated sediment, and it is widely used for estimating sediment yield (Goudie 1990; Van Dijk et al. 2003; Vigiak et al. 2006a, b). Rainfall simulators are used for creating artificial precipitation, the amount and rate of which can be controlled, over a land surface (Clarke and Walsh 2007). The rainfall simulator has an adjustable support, which was set to 400 mm above the ground surface. The simulator produces elongate drops with a diameter of 5.9 mm and a terminal velocity of 6 mm per minute. A Gerlach trough was installed in a shallow trench directly beneath the rainfall simulator in a ~0.9-m<sup>2</sup> study plot (Fig. 3). Before rainfall simulation, the plots were treated by removal of leaf litter and pre-wetting of the soil surface for approximately 30 s at an intensity of 1 mm per minute using a watering can. The reason for this pre-treatment was to control for temporal variations in antecedent conditions, such as seasonal litter accumulation and moisture variability. Although leaf litter is important for protecting the soil surface, it is not spatially contiguous in the study area, so removal of the litter from the study plots ensures that field experiments at different locations are comparable. Two synthetic rainstorms were generated using the rainfall simulator at each sampling location. Both simulated precipitation events had durations of 15 min. The first had an intensity of 2.1 mm per minute (hereafter “more intense”) for a total of 31.5 mm of



**Fig. 3** Field experiment setup with portable rainfall simulator and Gerlach trough

precipitation over the course of the event. The second had an intensity of 1.4 mm per minute (hereafter “less intense”) for a total of 21 mm of precipitation over the course of the event. The “more intense” precipitation event is the equivalent of the rainfall event of 15-min duration with a recurrence interval of 10 years (31.5 mm), and the “less intense” event is similar to a rainfall event of 15-min duration with a recurrence interval of one year (20.3 mm), based on precipitation frequency estimates for West Blocton, Alabama, the nearest weather station to the study sites (NWS 2015). The runoff and sediment generated by the rainfall simulator experiments were collected in the Gerlach trough and dried and weighed in the laboratory. Slope measurements were also made in the field at each sampling location using an Abney level.

Table 2 contains basic data about the sampling locations, including the results of the laboratory analysis of soil samples and characteristics of the watershed based on geospatial datasets. The site in the Valley and Ridge province of the upper watershed (Grants Mill) was dominated

**Table 2** Characteristics of sampling locations

Site name	Site code	% sand	% silt	% clay	% organic matter	Lithology	Slope angle (°)	Land cover
Grants Mill Road 1	GM1	83	10	7	3.2	Shale	9	Deciduous forest
Grants Mill Road 2	GM2	84	12	4	6.7	Shale	17	Deciduous forest
Grants Mill Road 3	GM3	72	16	12	7.9	Shale	24	Deciduous forest
National Wildlife Refuge 1a	NWR1a	89	6	5	12.0	Shale	3	Deciduous forest
National Wildlife Refuge 1b	NWR1b	70	11	19	8.2	Shale	25	Deciduous forest
National Wildlife Refuge 1c	NWR1c	72	11	17	10.8	Shale	6	Evergreen forest
National Wildlife Refuge 2a	NWR2a	72	11	17	12.1	Shale	31	Deciduous forest
National Wildlife Refuge 2b	NWR2b	72	13	15	11.1	Shale	20	Deciduous forest
National Wildlife Refuge 2c	NWR2c	76	12	12	27.9	Shale	19	Deciduous forest
Bibb County Glades 1	BCG1	91	5	4	7.9	Dolostone (dolomite)	25	Evergreen forest
Bibb County Glades 2	BCG2	84	12	4	11.6	Dolostone (dolomite)	6	Mixed forest
Bibb County Glades 3	BCG3	76	20	4	7.8	Dolostone (dolomite)	3	Mixed forest
Pratt's Ferry 1	PF1	86	5	9	2.7	Dolostone (dolomite)	24	Evergreen forest
Pratt's Ferry 2	PF2	80	7	13	8.7	Dolostone (dolomite)	28	Evergreen forest
Pratt's Ferry 3	PF3	68	18	14	13.1	Dolostone (dolomite)	27	Evergreen forest
Perry Lakes 1	PL1	93	2	5	0.4	Beach sand	3	Cultivated crops
Perry Lakes 2	PL2	85	1	14	5.7	Beach sand	0	Woody wetlands
Perry Lakes 3	PL3	72	10	18	7.9	Beach sand	0	Woody wetlands
Sprott Landing 1	SL2	60	17	23	10.4	Beach sand	0	Woody wetlands
Sprott Landing 2	SL3	74	17	9	4.8	Beach sand	6	Woody wetlands
Sprott Landing 3	SL1	89	4	7	0.6	Beach sand	3	Developed, low-intensity

Soil characteristics are for the A-horizon only

by deciduous forest, shale lithology, loamy fine sand soils, and average slopes of 17°. The two sites on the Gulf Coastal Plain of the lower watershed (Perry Lakes and Sprott Landing) were mostly dominated by evergreen forest and woody wetlands, with some cultivated crops and low-intensity development. The lithology for these lower sites was alluvial sand, the soil types were mostly sandy loam, and average slope was 2°. For the transitional Fall Line sites (National Wildlife Refuge 1 and 2, Bibb County Glades, Pratt's Ferry), the dominant land use was forest (deciduous, evergreen, and mixed), the dominant lithologies were shale and dolostone, the dominant soil type was sandy loam, and the average slope was 18°.

### Laboratory methods

Soil samples were taken from each identifiable horizon within a soil pit approximately 1 m deep from each of the 21 sampling locations. The pits were dug until regolith was encountered, which was generally around 1 m. Samples were taken from each visible horizon on the profile, which generally consisted of an A-horizon and B-horizon, with an E horizon visible at several of the sites in the lower watershed. The soil samples were analyzed in the

laboratory for particle size, organic matter content, and dry bulk density. Each sample was analyzed individually, but because sediment yield is presumably controlled most strongly by near-surface soil characteristics, only samples from the A-horizon were included in the modeling portion of this study. First, the samples were pre-processed by oven drying and sieving to remove material greater than 2 mm in diameter. Particle-size analysis was performed using standard hydrometer techniques, organic matter content analysis using loss-on-ignition techniques in a furnace, and bulk density analysis using the gravimetric method (NRCS 2014). The results included the percent sand, silt, clay, and organic matter, and the dry bulk density in grams per cubic centimeter, for each soil sample.

### Analysis methods

Data from the rainfall simulator experiments and soil samples, as well as existing geospatial datasets, were used to evaluate the relative sensitivity of sediment yield to soil and watershed characteristics under a range of precipitation intensities. An empirical event-based model was developed that relates this sediment yield to precipitation intensity, soil characteristics, and watershed variables. Linear and

nonlinear (e.g., logarithmic) regression models are an established analysis technique for sediment yield data (Weber et al. 1976; Skopp and Daniel 1978). Because ordinary least squares regression fails when parametric assumptions are not met, partial least squares (PLS) regression was used to construct the models, as implemented in JMP Pro 12:

$$\begin{aligned} X &= TP^T + E \\ Y &= UQ^T + F \end{aligned} \quad (1)$$

where  $X$  is an  $n \times m$  matrix of predictors;  $Y$  is an  $n \times p$  matrix of responses;  $T$  and  $U$  are  $n \times l$  matrices that are, respectively, projections of  $X$  and  $Y$ ;  $P$  and  $Q$  are, respectively,  $m \times l$  and  $p \times l$  orthogonal loading matrices; and matrices  $E$  and  $F$  are the error terms (Wold et al. 2001). The advantage of PLS regression is that it is robust with respect to observations that are limited in number, to a large number of independent variables, and to independent variables that are highly correlated with one another (i.e., that have a high degree of multicollinearity), all of which were characteristics of the data used in this paper (Cassel et al. 1999; Wu et al. 2009). PLS regression is similar to principal components analysis in that it uses a latent variable approach, but PLS fits a linear regression model to the data by projecting the dependent and independent variables to a new space that maximizes the multidimensional variance in the dependent variable relative to the multidimensional variance in the independent variables (Wold et al. 2001). After the PLS model is fit, the variables can be transformed back to their original space for use in predictive modeling. Recent examples of PLS modeling applications in sediment transport include studies on the effects of land cover on soil erosion and sediment yield (Shi et al. 2013), impacts of land-use change on streamflow and sediment yield (Yan et al. 2013), and controls on runoff and suspended-sediment yield during rainfall events (Fang et al. 2015).

Sediment yield, as the dependent variable in the PLS regression models, was defined as the dry mass of sediment collected from the Gerlach troughs during the rainfall simulator experiments. The independent variables included percent sand, silt, clay, and organic matter content of the solum (excluding leaf litter), and dry bulk density, from laboratory analysis of field samples; slope angle from field measurements; saturated hydraulic conductivity and available water capacity from the State Soils Geographical Database (STATSGO2) (NRCS 2015); and dummy variables for physiographic provinces (USGS 2015), lithology (NGMD 2015), soil series (NRCS 2015), and land cover (MRLC 2015). PLS regression models were developed separately for the “more intense” and “less intense” rainfall simulator experiments. The purpose of separating the results from the two experiments was to determine

whether different variables were significant in controlling sediment yield from high-intensity events as compared to more moderate events.

The empirical PLS-based model was applied to the entire Cahaba River watershed in ArcMap 10.2 using geospatial data from the National Elevation Dataset (NED 2015) for topographic variables, the National Geologic Map Database (NGMD 2015) for geologic variables, STATSGO2 for soil variables (NRCS 2015), and the National Land Cover Database (NLCD) for land-use and land-cover variables (MRLC 2015). The result was spatially explicit estimates of sediment yield associated with “more intense” and “less intense” precipitation events for each 10-digit Hydrologic Unit Code (HUC10) sub-basin in the Cahaba River watershed. These maps were intended only to identify potential hotspots of sedimentation for the purpose of determining possible spatial controls on the distribution of sediment sources.

## Results

### PLS model development

Table 3 shows the PLS models that were fitted to the “more intense” and “less intense” rainfall simulator experiment data. The “more intense” model identified two latent variables as the number of factors that minimized the root mean residual sum of squares. This optimal model cumulatively explained 41 % of the variance in sediment yield. The significant variables included in the final model were percent sand and slope, which were positively correlated with sediment yield, and percent clay and organic matter, which were negatively correlated with sediment yield (Fig. 4). Most of the significant variables were those that vary at highly local scales, namely soil and slope characteristics. For the “less intense” model, four factors were optimal and the model explained 73 % of the variance in sediment yield. The amount of variance explained by the independent variables was, therefore, greater for the “less intense” than the “more intense” model. The significant variables in the “less intense” model were percent sand, percent clay, and slope, which were all positively correlated with sediment yield; percent silt, percent organic matter, and saturated hydraulic conductivity, which were all negatively correlated with sediment yield; lithology, with the highest sediment yield from the dolostone-dominated sites; and land cover, with the highest sediment yield from evergreen forest (Figs. 4, 5). A greater number of watershed variables were found to be significant in explaining variance in sediment yield for the “less intense” model compared to the “more intense” model.

**Table 3** Properties of the “more intense” and “less intense” event-based PLS regression models

“More intense”	
Cumulative $R^2$	0.41
Number of factors	2
<i>Variable</i>	<i>Coefficient</i>
Intercept	3.17
Percent sand	0.18
Percent clay	−0.05
Percent organic matter	−0.24
Slope	0.22
“Less intense”	
Cumulative $R^2$	0.73
Number of factors	4
<i>Variable</i>	<i>Coefficient</i>
Intercept	8.53
Percent sand	0.13
Percent silt	−0.57
Percent clay	0.20
Percent organic matter	−0.32
Lithology	2.21
Land cover	0.86
Slope	0.31
Saturated hydraulic conductivity	−0.11

### Spatially explicit PLS models

Figure 6 shows the results of the spatially explicit event-based PLS model for the “more intense” and “less intense” events. These maps show the estimated mass of sediment eroded from a study plot the size of the plot used in the rainfall simulator experiments ( $\sim 0.9 \text{ m}^2$ ) and can be considered a relative rather than an absolute measure of erosion risk in the watershed. In order to make the values congruent with a watershed-scale analysis, these plot-scale estimates were summed to produce total loads of sediment in kilograms for each HUC10 sub-watershed of the Cahaba River watershed. The “less intense” map shows much greater spatial heterogeneity in its projections of potential event sediment load than the “more intense” map, and both indicate higher sediment load potential in the lower portion of the watershed. Figure 7 shows these simulated potential loads, as well as yields that are normalized by drainage area and loads normalized by river discharge for sub-basins in which gage data are available. When normalized by drainage area, the Lower Cahaba River has the highest potential event sediment load, but the sediment load potential is highest for the Cahaba River headwaters when normalized by mean discharge.

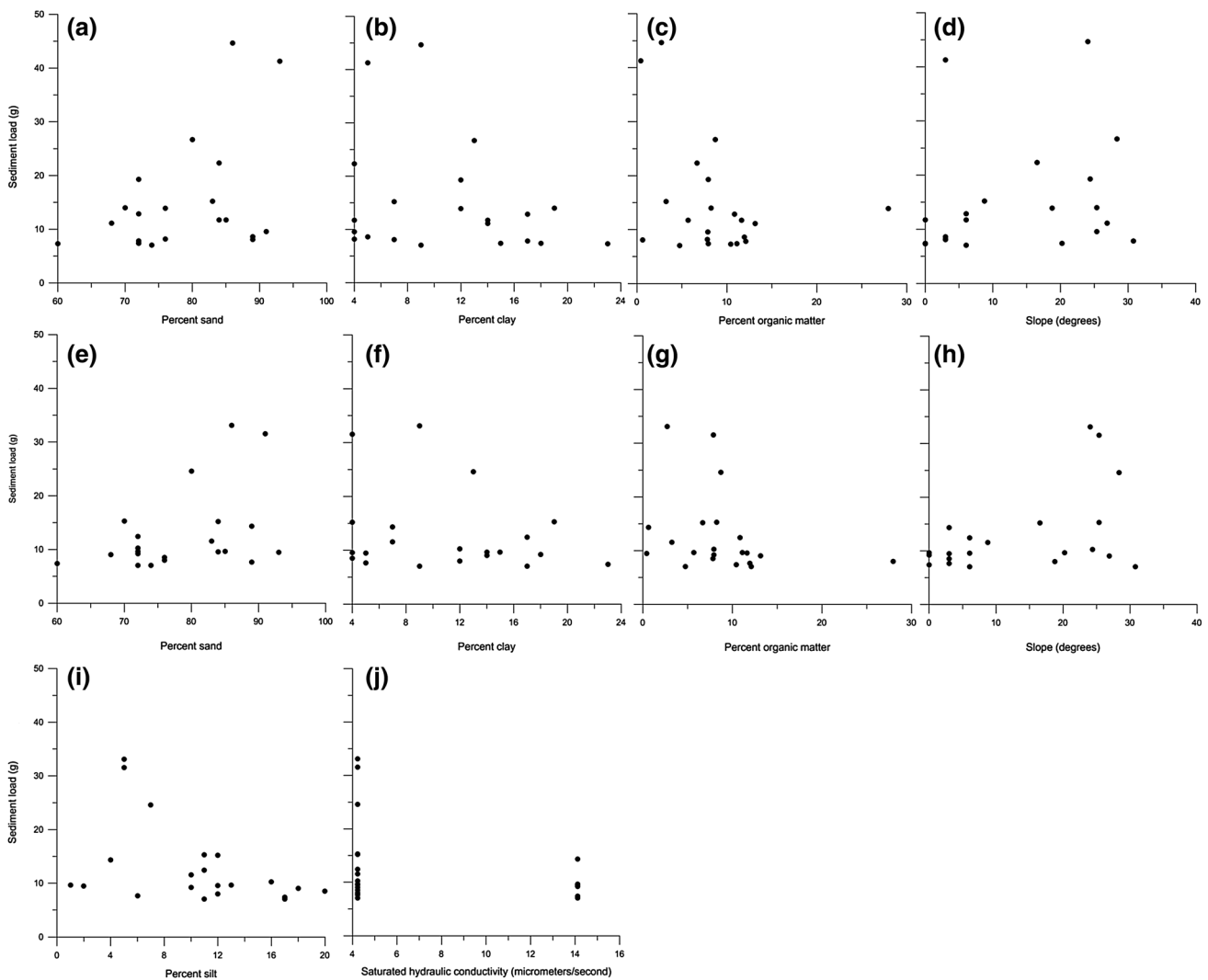
## Discussion

### PLS model development

The fit of the PLS regression models ranged from a cumulative  $R^2$  of 0.41 for the “more intense” event model to 0.73 for the “less intense” event model. Only two latent variables were retained as factors in the “more intense” model compared to four in the “less intense” model, which means that there were more dimensions of variance (i.e., a more complex underlying latent variable structure) in the “less intense” model. A possible explanation could be that, in the “more intense” model, the high precipitation intensity resulted in uniformly high sediment transport. In other words, when rainfall is extremely intense, sediment tends to be eroded at high rates regardless of the soil or land-cover characteristics. In the “less intense” model, meanwhile, subtle variations in soil and watershed characteristics had more of an influence on the variation in sediment yield, because when rainfall rates are relatively low, highly erodible surfaces will tend to erode much more than more stable surfaces. This idea is supported by observations that, at high precipitation intensities, hillslope sediment yield becomes less sensitive to slope (Kang et al. 2001) and vegetation characteristics (Li et al. 2012; Zhang et al. 2014). The fact that the “less intense” model was more highly fitted (i.e., retained more latent variables) than the “more intense” model explains the higher cumulative  $R^2$  for the “less intense” model.

Another difference between the “more intense” and “less intense” event models was the variables that were significant once transformed back into the original data space. This difference is important because it indicates what the leading controls on sediment yield are under different precipitation intensities. For the “more intense” model, there was a significant positive correlation with percent sand, which is the expected relationship because sand lacks cohesion and is easily dislodged by rainsplash erosion. There was also a positive correlation with slope, which again is as expected because the velocity of slope-wash is greater on steeper slopes and materials are closer to their angle of repose. Finally, there were negative correlations with percent clay and percent organic matter, which are materials that add cohesion (Cai et al. 2012). For the “less intense” model, percent sand and slope were still positively correlated with hillslope sediment yield, and percent organic matter was still negatively correlated. In the “less intense” model, however, percent clay was positively correlated with sediment yield, possibly because the slower rainfall rate allows more of the incoming precipitation to infiltrate and saturate the clays, rather than immediately generating runoff as in the “more intense”





**Fig. 4** Actual dry sediment load captured in Gerlach troughs during “more intense” rainfall simulator field experiments, showing the relationship between sediment load and **a** percent sand; **b** percent clay; **c** percent organic matter; **d** slope; actual dry sediment load

captured in Gerlach troughs during “less intense” rainfall simulator field experiments, showing the relationship between sediment load and **e** percent sand; **f** percent clay; **g** percent organic matter; **h** slope; **i** percent silt; and **j** saturated hydraulic conductivity

experiments. Saturated clays behave more like a liquid and lose cohesion relative to unsaturated clays (Dunster 2011). This interpretation is also supported by the negative correlation of saturated hydraulic conductivity with sediment yield in the “less intense” model, suggesting that when the incoming rainfall is able to infiltrate and be conducted through the soil, less runoff and soil loss occurs.

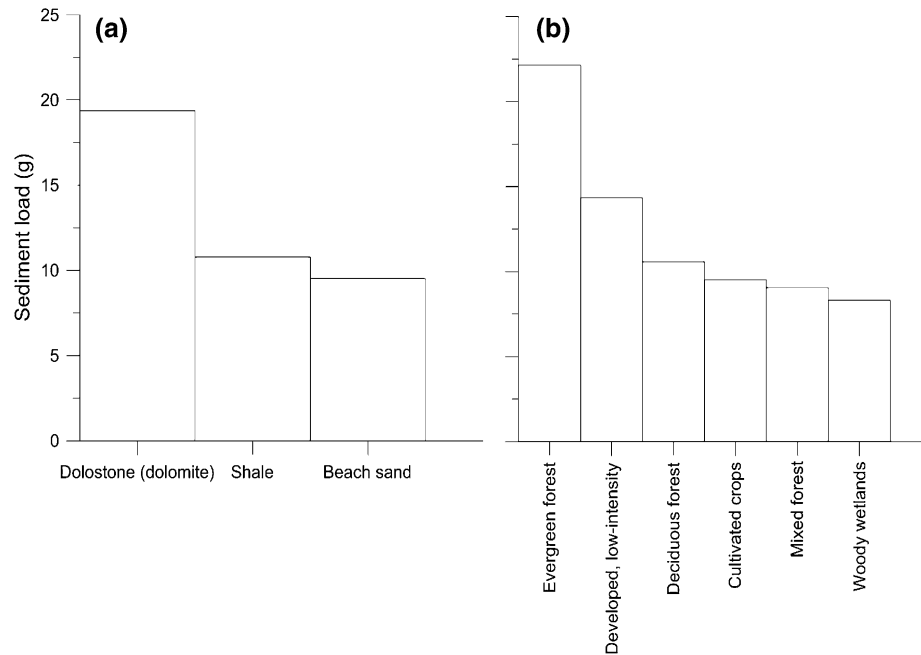
In the “less intense” PLS model, the highest yield was associated with the land cover of evergreen forest. This finding is contrary to expectations that sediment yield would be lower from forested land cover compared to cropland or developed land, because of less runoff from forested areas and more vegetation to contribute to slope stability. The reason measured sediment yield was higher from forested land cover is likely an artifact of the relationship between land cover and slope. Of all the land-

cover categories, the sites with evergreen forest had the steepest slopes (average of 22°), and the second steepest was for deciduous forest (average of 18°). The sites in the remaining land-cover categories all had average slopes of less than 5°. The apparent relationship between forested land cover and higher sediment yield, therefore, was actually the result of steeper areas tending to remain forested because they are unsuitable for other uses, such as agriculture or urban development.

**Spatially explicit PLS models**

For this study, only soil loss from hillslopes was measured in the field, not sediment storage, which commonly occurs in hillslope concavities, at the toe of slopes, or on floodplains (Kaste et al. 2006). Because the PLS models did not

**Fig. 5** Actual dry sediment load captured in Gerlach troughs during “less intense” rainfall simulator field experiments, showing the relationship between sediment load and **a** lithology; and **b** land cover

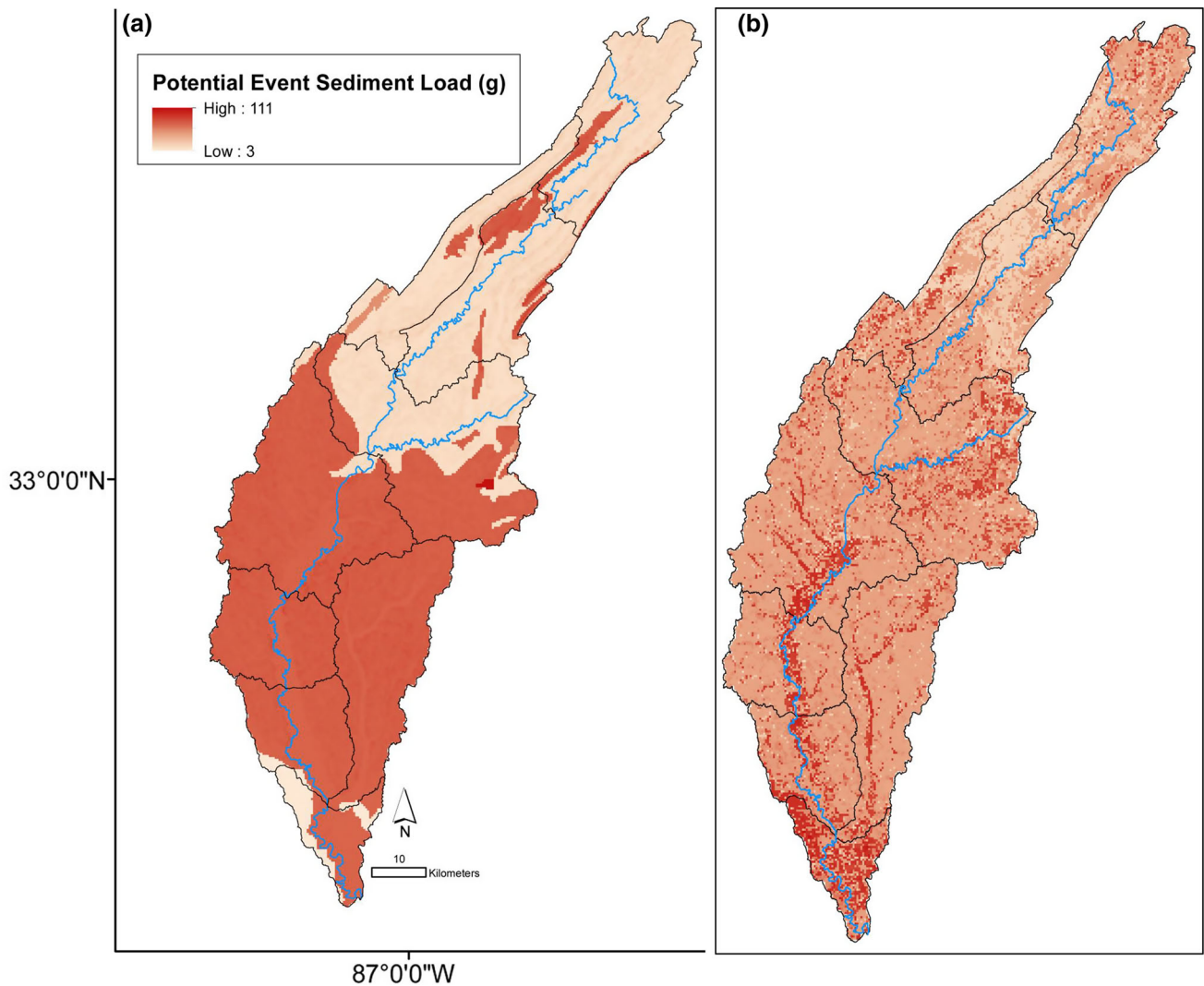


incorporate these storage effects, they could estimate only sediment eroded from hillslopes at the plot scale during individual precipitation events. Also, only hillslope sources of sediment were considered here, not in-channel or floodplain erosion. The results of the spatially explicit PLS models, therefore, should be interpreted as potential event sediment yield that indicates the relative sensitivity of different parts of the watershed to soil loss.

The spatial pattern of the PLS-modeled “more intense” potential event hillslope sediment yield included generally higher potential sediment yield in the lower Gulf Coastal Plain portion of the watershed compared with the upper Valley and Ridge portion of the watershed. This finding is contrary to expectations, given that only the upper reaches of the Cahaba River are listed for siltation, not the lower reaches (ADEM 2013). The likely reason is that the PLS models did not sufficiently account for the urban land use in the upper watershed. Because of site access restrictions, only one urban site was included in the fieldwork and that was a low-intensity urban site. There was therefore not sufficient variability in land cover among the sites for the model to strongly predict sediment yield in response to land cover, and land cover was retained as a significant variable only in the “less intense” event model. The PLS models can, therefore, be considered essentially as “natural” sediment yield maps; that is, they generally show which sites have the greatest potential for sediment yield in the absence of human modifications, based on soil and watershed characteristics. Without the anthropogenic influence, it is more reasonable to expect that sediment yield would be higher in the lower watershed, which is dominated by unconsolidated alluvial materials, rather than

the upper watershed, which is dominated by shale. In addition, potential soil loss is likely to be much lower than the actual sediment yield delivered to river systems (Kamaludin et al. 2013). Accounting for sediment storage on the floodplain could largely account for the difference between the upper and lower watershed in their potential hillslope sediment yield and actual river sediment concentrations.

For the PLS-modeled “less intense” hillslope sediment yield map, the same general pattern holds in which there was higher potential sediment yield in the lower watershed and lower sediment yield in the upper watershed. The most striking difference between the “more intense” and “less intense” event maps is that the “less intense” map displays much greater spatial heterogeneity in its estimates of sediment yield. The reason is that more variables were retained in the “less intense” PLS model, so the estimates of sediment yield were responding to finer-scale variation in the soil and watershed characteristics. Another difference between the two event maps is that the “less intense” map has a greater range of variability in estimated potential sediment yield, with both a lower minimum and a higher maximum sediment yield. The lower minimum sediment yield is as expected, because low-intensity rainfall events are likely to generate less rainsplash erosion and slopewash (Mandal et al. 2005). As for the higher maximum, in one-third of the rainfall simulator experiments (seven out of 21), there actually was higher sediment yield from the “less intense” than the “more intense” event. A qualitative observation made during these experiments was that, in some cases, the precipitation was so intense that the rainsplash impact created small depressions in the surface of

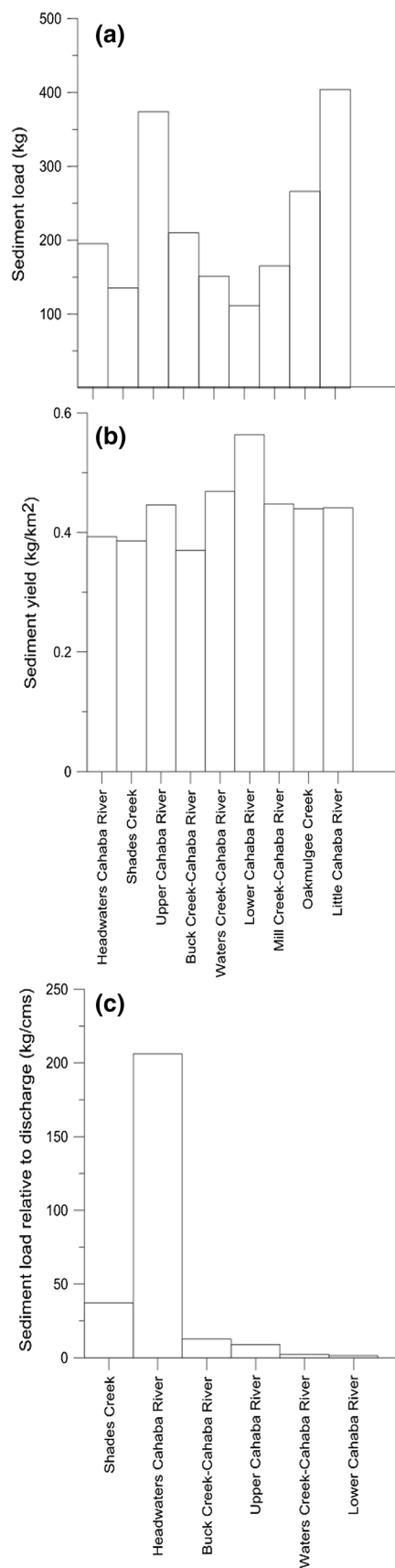


**Fig. 6** Event-based PLS estimates of sediment load from  $\sim 0.9\text{-m}^2$  study plot for **a** “more intense” rainfall and **b** “less intense” rainfall

the soil, which then collected additional precipitation that would otherwise contribute to slopewash. Such surface storage occurred less often during the “less intense” rainfall simulator experiments. Probably the most significant factor in explaining the larger range of estimated sediment yield for the “less intense” event is that the “less intense” PLS model simply contains more variables and a higher degree of spatial variability, which allows it to simulate highly localized hotspots of potential sediment yield. In all experiments, the rainfall simulation was started almost immediately after pre-wetting of the study plot, so the time between wetting and simulation is unlikely to be a factor in the variability between experiments.

The analysis of the PLS modeling results by HUC10 sub-basin reveals that, for both the “more intense” and “less intense” PLS models, the sub-basin with the highest total potential hillslope sediment load was the Little Cahaba River. For both models, the sub-basin with the

lowest estimated sediment load was the Lower Cahaba River. Normalized by drainage area, the Lower Cahaba River had the highest sediment yield in both models. In the “more intense” model, the sub-basin with the lowest area-normalized sediment yield was Shades Creek, while the lowest for the “less intense” model was Buck Creek—Cahaba River. Normalized by mean annual discharge, however, the sub-basin with the highest sediment load (of those that have gaging stations) was Headwaters Cahaba River for both models, and the lowest was the Lower Cahaba River for both models. This finding is consistent with the fact that the upper reaches of the Cahaba River are listed for siltation, while the lower reaches are not (ADEM 2013). Although the total amount of potential sediment yield may be greater in the lower alluvium-dominated watershed than in the upper bedrock-dominated watershed, river discharge increases more rapidly downstream than the simulated potential sediment yield does (Leopold and



**Fig. 7** Event-based PLS estimates by sub-basin under “less intense” rainfall, for **a** total sediment load; **b** sediment yield (sediment load normalized by drainage area); and **c** sediment load normalized by mean annual river discharge (for sites with gaging stations only). River discharge data are from NWIS (2015) and include the following gaging stations: Shades Creek near Greenwood, Alabama (02423630); Cahaba River at Trussville, Alabama (02423130, Headwaters Cahaba River); Cahaba River near Helena, Alabama (02423555, Buck Creek—Cahaba River); Cahaba River at Centreville, Alabama (02424000, Upper Cahaba River); Cahaba River near Suttle, Alabama (02424590, Waters Creek—Cahaba River); and Cahaba River near Marion Junction, Alabama (02425000, Lower Cahaba River)

Maddock 1953). Even if more sediment is capable of entering the lower Cahaba River from surrounding hillslopes, the increased discharge in the lower river means that the sediment concentration is likely to be lower than in the upper Cahaba River. Also, the PLS models did not account for in-channel sources of sediment such as bank failures, which often contribute a large portion of the total sediment load (Ismail 2000). These results support the assumption that excessive sedimentation is more likely to be a water-quality problem in the upper Cahaba River watershed, independently of the different land use/land cover in different parts of the watershed.

## Conclusion

Rainfall simulator field experiments were used to examine the role of soil and watershed characteristics in controlling sediment yield under a range of precipitation intensities. The field data, along with existing geospatial datasets, were used to construct partial least squares (PLS) models relating soil and watershed characteristics to sediment yield under both high- and moderate-intensity simulated precipitation events. These PLS models were then used to examine spatial patterns of potential event sediment yield for the Cahaba River watershed and its sub-basins. The cumulative  $R^2$  of the optimized PLS model was greater for the “less intense” than the “more intense” rainfall simulator experiments because of the greater number of variables retained. Variables that were consistently significant predictors of sediment yield in the PLS models included percent sand, percent clay, percent organic matter, and slope. The spatially explicit estimates of potential sediment yield were higher for the lower than the upper part of the watershed, because of under-sampling of urban land cover and larger areas of unconsolidated sediment in the lower watershed. The “less intense” event PLS model had a higher spatial resolution and a greater range of potential sediment-yield estimates than the “more intense” model,



because it was more highly fitted and retained a greater number of variables. Finally, an analysis of the PLS-estimated sediment yield by sub-basin revealed that sub-basins in the lower part of the watershed generally had greater potential sediment load. However, sub-basins in the upper watershed had greater potential sediment load when normalized by mean annual discharge, meaning that the upper Cahaba River is more vulnerable to high suspended-sediment concentrations that cause water-quality problems.

This research demonstrates that PLS regression models are an appropriate analysis tool for results of field experiments that use rainfall simulators to examine soil and watershed controls on sediment yield under different precipitation intensities. Future work should apply these methods to larger and more heterogeneous regions so that more generalizable relationships between watershed characteristics and sediment yield across multiple spatial scales can be established and so that the relative sensitivity of sediment yield to different climatic variables, such as precipitation intensity and antecedent soil moisture, can be examined. Such methods could be used for the development of best management practices to mitigate excessive sedimentation and to simulate the response of watershed sediment yield to future changes in climate and land use.

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**References**

Akbarzadeh A, Mehrjardi RT, Refahi HG, Rouhipour H, Gorji M (2009) Using soil binders to control runoff and soil loss in steep slopes under simulated rainfall. *Int Agrophys* 23:99–109

Alabama Department of Environmental Management (ADEM) (2013) Total maximum daily load (TMDL) for siltation and habitat alteration in the Upper Cahaba River Watershed (HUC 03150202), Bibb, Chilton, Jefferson, Shelby, St. Clair and Tuscaloosa Counties, Alabama. ADEM Water Division, Montgomery, AL

An J, Zheng F, Lu J, Li G (2012) Investigating the role of raindrop impacts on hydrodynamic mechanism of soil erosion under simulated rainfall conditions. *Soil Sci* 177:517–526. doi:10.1097/SS.0b013e3182639de1

An J, Zheng FL, Han Y (2014) Effects of rainstorm patterns on runoff and sediment yield processes. *Soil Sci* 179:293–303. doi:10.1097/SS.0000000000000068

Bathrellos GD, Gaki-Papanastassiou K, Skilodimou HD, Papanastassiou D, Chousianitis KG (2012) Potential suitability for urban planning and industry development using natural hazard maps and geological-geomorphological parameters. *Environ Earth Sci* 66:537–548. doi:10.1007/s12665-011-1263-x

Boix-Fayos C, de Vente J, Martínez-Mena M, Barberá GG, Castillo V (2008) The impact of land-use change and check-dams on catchment sediment yield. *Hydrol Process* 22:4922–4935. doi:10.1002/hyp.7115

Cai T, Li Q, Yu M, Lu G, Cheng L, Wei X (2012) Investigation into the impacts of land-use change on sediment yield characteristics in the upper Huaihe River basin, China. *Phys Chem Earth* 53–54:1–9. doi:10.1016/j.pce.2011.08.023

Cassel C, Hackl P, Westlund AH (1999) Robustness of partial least-squares method for estimating latent variable quality structures. *J Appl Stat* 26:435–446

Chanson H, Takeuchi M, Trevethan M (2008) Using turbidity and acoustic backscatter intensity as surrogate measures of suspended sediment concentration in a small subtropical estuary. *J Environ Manage* 88:1406–1460. doi:10.1016/j.jenvman.2007.07.009

Chappell A, Strong C, McTainsh G, Leys J (2007) Detecting induced in situ erodibility of a dust-producing playa in Australia using a bi-directional soil spectral reflectance model. *Remote Sens Environ* 106:508–524. doi:10.1016/j.rse.2006.09.009

Chighladze G, Kaleita A, Birrell S, Logson S (2012) Estimating soil solution nitrate concentration from dielectric spectra using partial least squares analysis. *Soil Sci Soc Am J* 76:1536–1547. doi:10.2136/sssaj2011.0391

Chousianitis K, Del Gaudio V, Sabatakakis N, Kavoura K, Drakatos G, Bathrellos GD, Skilodimou HD (2016) Assessment of earthquake-induced landslide hazard in Greece: from Arias intensity to spatial distribution of slope resistance demand. *B Seismol Soc Am* 106:174–188. doi:10.1785/0120150172

Clarke MA, Walsh RPD (2007) A portable rainfall simulator for field assessment of splash and slopewash in remote locations. *Earth Surf Proc Land* 32:2052–2069. doi:10.1002/esp.1526

Conforti M, Buttafuoco G, Leone AP, Auccelli PPC, Robustelli G, Scarciglia F (2013) Studying the relationship between water-induced soil erosion and soil organic matter using Vis-NIR spectroscopy and geomorphological analysis: a case study in southern Italy. *Catena* 110:44–58. doi:10.1016/j.catena.2013.06.013

Doerr SH, Shakesby RA, Walsh RPD (2000) Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Sci Rev* 51:33–65. doi:10.1016/S0012-8252(00)00011-8

Dunster K (2011) Dictionary of natural resource management. UBC Press, Vancouver

Durán Zuazo VH, Francia Martínez JR, García Tejero I, Rodríguez Pleguezuelo CR, Martínez Raya A, Cuadros Tavira S (2012) Runoff and sediment yield from a small watershed in southeastern Spain (Lanjarón): implications for water quality. *Hydrol Sci J* 57:1610–1625. doi:10.1080/02626667.2012.726994

El-Kaddah DN, Carey AE (2004) Water quality modeling of the Cahaba River, Alabama. *Environ Geol* 45:323–338. doi:10.1007/s00254-003-0890-2

Fang N, Shi Z, Chen F, Wang Y (2015) Partial least squares regression for determining the control factors for runoff and suspended sediment yield during rainfall events. *Water* 7:3925–3942. doi:10.3390/w7073925

Froehlich DC (2011) NRCS overland flow travel time calculation. *J Irrig Drain E* 137:258–262. doi:10.1061/(ASCE)JIR.1943-4774.0000287

Gholami L, Sadeghi SH, Homae M (2013) Straw mulching effect on splash erosion, runoff, and sediment yield from eroded plots. *Soil Sci Soc Am J* 77:268–278. doi:10.2136/sssaj2012.0271

Gilley JE, Woolhiser DA, McWhorter DB (1985) Interrill soil erosion—part I: development of model equations. *Trans Am Soc Agric Eng* 28:147–159

Goudie A (1990) *Geomorphological techniques*. Routledge, London

- Grauso S, Diodato N, Verrubbi V (2010) Calibrating a rainfall erosivity assessment model at regional scale in Mediterranean area. *Environ Earth Sci* 60:1597–1606. doi:10.1007/s12665-009-0294-z
- Griffiths PG, Hereford R, Webb RH (2006) Sediment yield and runoff frequency of small drainage basins in the Mojave Desert, U.S.A. *Geomorphology* 74:232–244. doi:10.1016/j.geomorph.2005.07.017
- Holifield Collins CD, Stone JJ, Cartic L III (2015) Runoff and sediment yield relationships with soil aggregate stability for a state-and-transition model in southeastern Arizona. *J Arid Environ* 117:96–103. doi:10.1016/j.jaridenv.2015.02.016
- Ismail WR (2000) The hydrology and sediment yield of the Sungai Air Terjun catchment, Penang Hill, Malaysia. *Hydrolog Sci J* 45:897–910. doi:10.1080/02626660009492391
- Jones DE (1967) Geology of the coastal plain of Alabama. Geological Society of America, New Orleans
- Jordán A, Martínez-Zavala A (2008) Soil loss and runoff rates on unpaved forest roads in southern Spain after simulated rainfall. *Forest Ecol Manag* 255:913–919. doi:10.1016/j.foreco.2007.10.002
- Kamaludin H, Lihan T, Ali Rahman Z, Mustapha MA, Idris WMR, Rahim SA (2013) Integration of remote sensing, RUSLE, and GIS to model potential soil loss and sediment yield (SY). *Hydrol Earth Syst Sci Dis* 10:4567–4596. doi:10.5194/hessd-10-4567-2013
- Kang S, Zhang L, Song X, Zhang S, Liu X, Liang Y, Zheng S (2001) Runoff and sediment loss responses to rainfall and land use in two agricultural catchments on the Loess Plateau of China. *Hydrol Process* 15:977–988. doi:10.1002/hyp.191
- Kaste JM, Heimsath AM, Hohmann M (2006) Quantifying sediment transport across an undisturbed prairie landscape using cesium-137 and high resolution topography. *Geomorphology* 76:430–440. doi:10.1016/j.geomorph.2005.12.007
- Kidd JT, Shannon S (1978) Stratigraphy and structure of the Birmingham area, Jefferson County. Geological Society of Alabama, Tuscaloosa
- Kim J, Ivanov VY (2014) On the nonuniqueness of sediment yield at the catchment scale: the effects of soil antecedent conditions and surface shield. *Water Resour Res* 50:1025–1045. doi:10.1002/2013WR014580
- Lamsal S (2009) Visible near-infrared reflectance spectroscopy for geospatial mapping of soil organic matter. *Soil Sci* 174:35–44. doi:10.1097/SS.0b013e3181906a09
- Lee G, Yu W, Jung K (2013) Catchment-scale soil erosion and sediment yield simulation using a spatially distributed erosion model. *Environ Earth Sci* 70:33–47. doi:10.1007/s12665-012-2101-5
- Leopold LB, Maddock T Jr (1953) The hydraulic geometry of stream channels and some physiographic implications. United States Geological Survey, Washington
- Li X, Niu J-Z, Li J, Xie B-Y, Han Y-N, Tan J-P, Zhang Y-H (2012) Characteristics of runoff and sediment generation of forest vegetation on a hill slope by use of artificial rainfall apparatus. *J For Res* 23:419–424. doi:10.1007/s11676-012-0279-8
- Liermann S, Beylich AA, van Welden A (2012) Contemporary suspended sediment transfer and accumulation processes in the small proglacial Sætrevatnet sub-catchment, Bødalen, western Norway. *Geomorphology* 167–168:91–101. doi:10.1016/j.geomorph.2012.03.035
- Mandal UK, Rao KV, Mishra PK, Vittal KPR, Sharma KL, Narsimlu B, Venkanna K (2005) Soil infiltration, runoff, and sediment yield from a shallow soil with varied stone cover and intensity of rain. *Eur J Soil Sci* 56:435–443. doi:10.1111/j.1365-2389.2004.00687.x
- Martínez-Zavala L, Jordán López A, Bellinfante N (2008) Seasonal variability of runoff and soil loss on forest road backslopes under simulated rainfall. *Catena* 74:73–79. doi:10.1016/j.catena.2008.03.006
- Molina A, Govers G, Poesen J, Van Hemelryck H, De Bièvre B, Vanacker V (2008) Environmental factors controlling variation in sediment yield in a central Andean mountain area. *Geomorphology* 98:176–186. doi:10.1016/j.geomorph.2006.12.025
- Multi-Resolution Land Characteristics Consortium (MRLC) (2015) National Land Cover Database (NLCD). <http://www.mrlc.gov/>. Accessed 8 Oct 2015
- Nadal-Romero E, Latron EJ, Martí-Bono C, Regüés D (2008) Temporal distribution of suspended sediment transport in a humid Mediterranean badland area: the Araguás catchment, Central Pyrenees. *Geomorphology* 97:601–616. doi:10.1016/j.geomorph.2007.09.009
- National Elevation Dataset (NED) (2015) The National Map. <http://nationalmap.gov/elevation.html>. Accessed 8 Oct 2015
- National Geologic Map Database (NGMD) (2015) The National Geologic Map Database. [http://ngmdb.usgs.gov/ngmdb/ngmdb\\_home.html](http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html). Accessed 8 Oct 2015
- National Water Information System (NWIS) (2015) USGS Surface-Water Monthly Statistics for the Nation. [http://waterdata.usgs.gov/nwis/monthly/?referred\\_module=sw](http://waterdata.usgs.gov/nwis/monthly/?referred_module=sw). Accessed 9 Oct 2015
- National Weather Service (NWS) (2015) Precipitation Frequency Data Server (PFDS). <http://hdsc.nws.noaa.gov/hdsc/pfds/>. Accessed 8 Oct 2015
- Natural Resources Conservation Service (NRCS) (2014) Soil survey field and laboratory methods manual. Soil Survey Investigation Report No. 51, Version 2.0. United States Department of Agriculture, Lincoln, NE
- Natural Resources Conservation Service (NRCS) (2015) Description of STATSGO2 Database. [http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2\\_053629](http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053629). Accessed 8 Oct 2015
- Nearing MA (2001) Potential changes in rainfall erosivity in the U.S. with climate change during the 21st century. *J Soil Water Conserv* 56:229–232
- Nu-Fang F, Zhi-Hua S, Lu L, Cheng J (2011) Rainfall, runoff, and suspended sediment delivery relationships in a small agricultural watershed of the Three Gorges area, China. *Geomorphology* 135:158–166. doi:10.1016/j.geomorph.2011.08.013
- Paige GB, Stone JJ, Guertin DP, Lane LJ (2002) A strip model approach to parameterize a coupled Green-Ampt kinematic wave model. *J Am Water Resour As* 38:1363–1377
- Pan C, Shangguan Z (2006) Runoff hydraulic characteristics and sediment generation in sloped grassplots under simulated rainfall conditions. *J Hydrol* 331:178–185. doi:10.1016/j.jhydrol.2006.05.011
- Pierson FB, Carlson DH, Spaeth KE (2001) A process-based hydrology submodel dynamically linked to the plant component of the simulation of production and utilization on rangelands SPUR model. *Ecol Model* 141:241–260. doi:10.1016/S0304-3800(01)00277-0
- Pierson FB, Moffet CA, Williams CJ, Hardegree SP, Clark PE (2009) Prescribed-fire effects on rill and interrill runoff and erosion in a mountainous sagebrush landscape. *Earth Surf Proc Land* 34:193–203. doi:10.1002/esp.1703
- PRISM Climate Group (2016) 30-Year Normals. <http://www.prism.oregonstate.edu/normals/>. Accessed 6 June 2016
- Rodríguez-Caballero E, Cantón Y, Chamizo S, Lázaro R, Escudero A (2013) Soil loss and runoff in semiarid ecosystems: a complex interaction between biological soil crusts, micro-topography, and hydrological drivers. *Ecosystems* 16:529–546. doi:10.1007/s10021-012-9626-z

- Rozos D, Skilodimou HD, Loupasakis C, Bathrellos GD (2013) Application of the revised universal soil loss equation model on landslide prevention: an example from N. Euboea (Evia) Island, Greece. *Environ Earth Sci* 70:3255–3266. doi:10.1007/s12665-013-2390-3
- Scharrón CER (2010) Sediment production from unpaved roads in a sub-tropical dry setting: Southwestern Puerto Rico. *Catena* 82:146–158. doi:10.1016/j.catena.2010.06.001
- Schotz A (2016) Plant Communities of Alabama. <http://www.encyclopediaofalabama.org/article/h-2060>. Accessed 6 June 2016
- Seeger M (2007) Uncertainty of factors determining runoff and erosion processes as quantified by rainfall simulations. *Catena* 71:56–67. doi:10.1016/j.catena.2006.10.005
- She D, Fei Y, Liu Z, Liu D, Shao G (2014) Soil erosion characteristics of ditch banks during reclamation of a saline/sodic soil in a coastal region of China: field investigation and rainfall simulation. *Catena* 121:176–185. doi:10.1016/j.catena.2014.05.010
- Shi ZH, Ai L, Li X, Huang XD, Wu GL, Liao W (2013) Partial least-squares regression for linking land-cover patterns to soil erosion and sediment yield in watersheds. *J Hydrol* 498:165–176. doi:10.1016/j.jhydrol.2013.06.031
- Skopp J, Daniel TC (1978) A review of sediment predictive techniques as viewed from the perspective of nonpoint pollution management. *Environ Manage* 2:39–53
- Southeast Regional Climate Center (SERCC) (2016) Alabama state average precipitation data. [http://www.sercc.com/climateinfo\\_files/monthly/Alabama\\_prpc\\_DivNew.htm](http://www.sercc.com/climateinfo_files/monthly/Alabama_prpc_DivNew.htm). Accessed 6 June 2016
- Svoray T, Ben-Said S (2010) Soil loss, water ponding and sediment deposition variations as a consequence of rainfall intensity and land use: a multi-criteria analysis. *Earth Surf Proc Land* 35:202–216. doi:10.1002/esp.1901
- United States Department of Agriculture (USDA) (2016) Official Soil Series Descriptions (OSD) with Series Extent Mapping Capabilities. <https://soilseries.sc.egov.usda.gov/>. Accessed 6 June 2016
- United States Geological Survey (USGS) (2015) Physiographic Divisions of the Conterminous U.S. <http://water.usgs.gov/GIS/metadata/usgswrd/XML/physio.xml>. Accessed 8 Oct 2015
- Van Dijk AIJM, Bruijnzeel LA, Wiegman SE (2003) Measurements of rain splash on bench terraces in a humid tropical steepland environment. *Hydrol Process* 17:513–535. doi:10.1002/hyp.1155
- Vigiak O, Romanowicz RJ, van Loon EE, Sterk G, Beven KJ (2006a) A disaggregating approach to describe overland flow occurrence within a catchment. *J Hydrol* 323:22–40. doi:10.1016/j.jhydrol.2005.08.012
- Vigiak O, Sterk G, Romanowicz RJ, Beven KJ (2006b) A semi-empirical model to assess uncertainty of spatial patterns of erosion. *Catena* 66:198–210. doi:10.1016/j.catena.2006.01.004
- Wan L, Zhang XP, Ma Q, Zhang JJ, Ma TY, Sun YP (2014) Spatiotemporal characteristics of precipitation and extreme events on the Loess Plateau of China between 1957 and 2009. *Hydrol Process* 28:4971–4983. doi:10.1002/hyp.9951
- Weber JE, Fogel MM, Duckstein L (1976) Use of multiple regression models in predicting sediment yield. *Water Resour Bull* 12:1–17. doi:10.1111/j.1752-1688.1976.tb02634.x
- Wischmeier WH, Smith DD (1978) Predicting rainfall erosion losses: a guide to conservation planning. United States Department of Agriculture, Washington
- Wold S, Sjöström M, Eriksson L (2001) PLS-regression: a basic tool of chemometrics. *Chemometr Intell Lab* 58:109–130
- Wu C-H, Chen LH, Tsai Y-M (2009) Investigating importance weighting of satisfaction scores from a formative model with partial least squares analysis. *Soc Indic Res* 90:351–363. doi:10.1007/s11205-008-9264-1
- Wu L, Long T-Y, Liu X, Ma X-Y (2013) Modeling impacts of sediment delivery ratio and land management on adsorbed non-point nitrogen and phosphorus load in a mountainous basin of the Three Gorges reservoir area, China. *Environ Earth Sci* 70:1405–1422. doi:10.1007/s12665-013-2227-0
- Yan B, Fang NF, Zhang PC, Shi ZH (2013) Impacts of land use change on watershed streamflow and sediment yield: an assessment using hydrologic modelling and partial least squares regression. *Journal Hydrol* 484:26–37. doi:10.1016/j.jhydrol.2013.01.008
- Zhang X, Yu GQ, Li ZB, Li P (2014) Experimental study on slope runoff, erosion, and sediment under different vegetation types. *Water Resour Manag* 28:2415–2433. doi:10.1007/s11269-014-0603-5
- Zheng Z-C, He S-Q, Wu F-Q (2014) Changes of soil surface roughness under water erosion process. *Hydrol Process* 28:3919–3929. doi:10.1002/hyp.9939