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Sediment loss and its causes in Puerto Rico watersheds

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Abstract

A major environmental concern in the Commonwealth of Puerto Rico is increased sediment load to water reservoirs, to estuaries and finally to coral reef areas outside the estuaries. Sediment deposition has significantly reduced the storage capacity of reservoirs, and sediments, the associated contaminants and nutrients that are adsorbed, can stress corals and negatively impact reef health. Therefore, it is important to understand local soil erosion and sediment transport processes to better prevent and manage sediment loss. The main objective of this study was to determine the influence of landscape characteristics on sediment loss. We analyzed available precipitation and sediment data collected in Puerto Rico during the past three decades, and information on land use, soil properties and topography. Our partial least squares analysis was not very successful in identifying major factors associated with sediment loss due to the complexity of the study watersheds. However, the main factors causing sediment loss from ridge watersheds in Puerto Rico were mainly caused by interactions of development, heavy rainfall events (especially the hurricanes) and steep mountainous slopes associated with the ridges. These results improve our understanding of sediment loss resulting from changes in land use/cover within a Puerto Rico watershed, and will allow stakeholders to make more informed decisions about future land use planning.

1 Introduction

Water bodies and coastal areas around the world are threatened by increases in upstream sediment and nutrient runoff, influencing drinking water sources, aquatic species, and other ecologic functions and services of streams, lakes and coastal water bodies (Haycock and Muscutt, 1995; Verhoeven et al., 2006). Puerto Rico (PR) faces considerable challenges regarding sustainable land use and the effects of current land use on adjacent coastal ecosystems and the services they provide. Studies by scientists in PR have suggested that sediment contaminants have increased 5- to 10-fold

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since pre-colonial levels, with a 2- to 3-fold increase in the last 40–50 years (Sturm et al., 2012). The increased sediment contamination could originate from anthropogenic activities, such as agriculture and urban development, or from natural erosion (Tong and Chen, 2002; Gellis, 1993, 2013). The primary concern regarding increased sediment load to reservoirs is that sediment deposition has significantly reduced the storage capacity of reservoirs. This sedimentation can also reduce photosynthetic activity of aquatic plants and algae in these reservoirs, and increase water treatment costs for domestic and industrial uses (Estades Hernández et al., 1997). These sediments and the pollutants adsorbed to them can ultimately reach offshore reef areas and can stress or kill the corals that comprise the reef. Reduction of sediments reaching reservoirs and offshore reefs is key in the management and conservation of natural resources (Morgan, 1986).

Watershed-scale studies regarding the potential effect of land use changes on water quality are essential to minimize water pollution. Various studies have linked stream pollutants to landscape variables using process-based hydrological models (Jha et al., 2010; Kirsch et al., 2002; Ullrich and Volk, 2009; Hu et al., 2014) and/or statistical methods (Lenat and Crawford, 1994; Liu et al., 2009; Lopez et al., 2008; Mehaffey et al., 2005; Nash et al., 2009; Nie et al., 2011; Mbonimpa et al., 2014). Process based hydrologic models have been successfully used to characterize watershed processes and sources of stream pollutants, but these models require detailed input data, which may not be available for some areas. For instance, Hu et al. (2014) showed the difficulty of calibrating a SWAT model for the Guánica Bay, PR, watershed due to limited data for numerous reservoirs and dams in the basin. However, various studies have demonstrated statistical relationships between landscape metrics and water quality. For example, Lenat and Crawford (1994), using statistical models, found that urban land use is the highest contributor to sediment loss when they analyzed water samples from three watersheds each having a different dominant land use (forest, urban, agricultural) in the Piedmont ecoregion of North Carolina. Mbonimpa et al. (2014), using partial least squares (PLS) regression analysis, identified urban land use and agricultural land growing corn were associated with increases in total suspended sediment and total phosphorous in streams. The objective of this study was to evaluate the influence of landscape characteristics on levels of suspended sediments and identify factors that impact sediment loss using statistical methods. Identifying major factors causing sediment loss would help stakeholders make better decisions about future land use planning for sediment control.

2 Methodology

2.1 Study area

2.1.1 Landscape

Prior to European colonization of PR (16th century) almost the entire island area was covered with forests. It was not until the beginning of the 19th century that forests were cleared for planting sugarcane, coffee, cotton, and tobacco. Deforestation peaked in the 1940s with only 6 % of Puerto Rico remaining forested. Subsequently, islanders abandoned agriculture for manufacturing and service industries and by the 1990s forest covered about 32 % of the island area. These secondary forests regenerated from abandoned pastures and coffee plantations, and currently are a mix of native and non-native naturalized species (Chinea, 2002; Lugo and Helmer, 2004).

Many watersheds are located in the major coffee growing zone of PR. Historically these areas grew coffee under the shade of canopy trees, but in 1980s the government promoted sun-grown coffee to increase yield (Borkhataria et al., 2012). However, the market for shade coffee has rebounded. Canopy development for shading coffee, especially by leguminous plants improves the soil condition by supplying nutrients, increasing root penetrability through hardened subsoil layers, increasing soil organic matter, and increasing water percolation and soil protection. In this study, shade coffee plantations are classified as shrub because of their low canopy.

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2.1.2 Extreme weather events and effects

Puerto Rico receives an average of 1651 mm of precipitation annually, delivered by infrequent but high intensity rainfall events. Puerto Rico is located in the Caribbean hurricane belt and hurricanes are Puerto Rico's number one weather threat because of the damaging high winds, waves, and large volumes of rain. Six to ten hurricanes threaten this region annually, and some powerful hurricanes (e.g., Hugo – 1989, Hortense – 1996, Georges – 1998, Lenny – 1999, and Irene – 2011) have caused catastrophic damage to the environment. Various parts of PR also experience severe yearly storms that cause floods, tree falls and landslides (Nagle et al., 1999).

Rain intensity, duration, frequency and areal extent are the most important factors contributing to erosion (Jiang et al., 2008), thus hurricanes can be major causes of erosion. For example, Hurricane Georges passed over PR and dropped roughly 2.6 billion cubic meters of water (285 mm) on the island, of which 1 billion cubic meters (109 mm) were converted to run-off. This may have caused as much as 5–10 million metric tons of sediment (5–11 $t\,ha^{-1}$) to be discharged onto the coastal shelf with significant negative impact on coral reefs (Larsen and Webb, 2009); most of the sediment transport (62–99 %) occurred in a single day.

2.1.3 Erosion and sediment loss

Runoff generated from storm events of high intensity or long duration transport large quantities of SS. Annual SS loss in some PR watersheds can be as high as 130 $t\,ha^{-1}\,year^{-1}$. In addition, landslides triggered by heavy rainfall also contribute an average of 3 $t\,ha^{-1}\,year^{-1}$ into river channels (Zack and Larsen, 1994). Adding to the transport of SS is severe stream bank erosion which often occurs in sun-grown coffee growing areas (CWP, 2008).

Sediment can accumulate along rivers but much of it is transported into, and accumulates in reservoirs. Usually, reservoir design includes some additional volume to account for predicted sedimentation during the life of the reservoir. However, in many tropical dam designs, sediment load has typically been underestimated by not accounting for hurricanes, landslides (Nagle et al., 1999), land-use change, and natural instability of slopes. Further, reservoir dams built on small and steep watersheds are more vulnerable to sedimentation because the steep slopes reduces the time available for sediment to settle out on the land before reaching the reservoir (Nagle et al., 1999).

Management actions to reduce sediment loss are urgently needed in PR. Recent landscape trends show increasing use of conservation practices by farmers returning to shade grown coffee as new markets for shade-grown coffee arise and also as the increased reforestation of abandoned agriculture occurs (Chinea, 2002).

2.2 Data acquisition

Monthly precipitation data were obtained from the National Oceanic and Atmospheric Administration-National Climatic Data Center (NOAA-NCDC; http://www.ncdc.noaa.gov/cdo-web/search). There are thirty-three NOAA-NCDC weather stations located on the main island of PR (Fig. 1).

There are thirty-one United States Geological Survey (USGS) stations that monitor stream flow and SS in Puerto Rican watersheds (Fig. 1). To meet the assumption of independence of watersheds (observations) for regression analysis, nested watersheds (watersheds situated within larger watersheds) were not included in this analysis, leaving 20 independent watersheds with USGS monitoring (Table 1).

Digital Elevation Model (DEM), land use, and the Soil Survey Geographic Database (SSURGO) data were downloaded from the USGS (http://seamless.usgs.gov/), Multi-Resolution Land Characteristics Consortium (http://www.mrlc.gov/nlcd01_data.php) and the United States Department of Agriculture-Natural Resources Conservation Service (http://sdmdataaccess.nrcs.usda.gov/), respectively.

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2.3 Preliminary data analysis and ANOVA tests

Annual SS concentrations and load time series from the 20 independent USGS monitoring stations are presented in Figs. 2 and 3 for visual comparisons of SS concentrations and load among study watersheds. Suspended sediment (SS) load was normalized by dividing by the drainage area and expressed as $\mathrm{t\,ha^{-1}}$ and an ANOVA was used to determine the differences in annual SS concentrations and load among watersheds. Based on available monitoring periods, visual comparisons of SS concentrations and load from different watersheds and ANOVA tests, eleven USGS monitoring stations were selected for further partial least square (PLS) analysis to identify major factors contributing to sediment loss. The distributions (percent of total watershed area) of land use type (Table 2) and soil type (Table 3) for each watershed were determined by overlaying the National Land Cover Database (NLCD) 2001 land use map and SSURGO soil map onto the watershed boundaries. The majority land covers in the studied watersheds were evergreen forest and grassland/herbaceous (ranging from 50 to 100 %) (Table 2). Other land uses include developed (ranging from 0 to 47 %), pasture/hay (0 to 31 %) and scrub/shrub (0 to 7 %). Shade coffee plantations and secondary forests are both classified as shrub because of their low canopy.

Soils in the studied watersheds varied, but with the majority of the soils in the study watersheds being very to moderately deep, well drained, and very to moderately permeable. Soil properties such as erodibility, texture and hydraulic conductivity for each soil type were retrieved from the SSURGO soil database (Table 4) with their major soil series and their drainage properties (Table 5).

Land slope (terrain) was calculated using ArcMap (ArcGIS10) (Table 6). The study watersheds have steep slopes with means ranging from 15 to 40 % (Table 6). The majority of the individual slopes are in categories 9–25 % and 25–60 % (Table 6).

Thiessen Polygons, created from available weather stations using ArcMap (ArcGIS10), were overlaid onto the watershed boundary. Areal average precipitation was calculated for each watershed based on where the polygons fall in the water-

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sheds. We calculated the correlation between the calculated watershed precipitation and SS concentrations and load. Subsequently, Land use (Evergreen forest, Grassland/Herbaceous, Developed lands, Barren lands, Pasture/Hay, Scrub/shrub) and soil distribution (SSURGO soil types, Table 3), slope (Terrain mean slope, Terrain minimum slope, Terrain with slopes lower than 9 %, Terrain with slopes between 9–25 %, Terrain with slopes between 25–60 %, Terrain with slopes between 60–80 %, Terrain with slopes higher than 80 %) and calculated precipitation formed predictors for the loss of sediments from each watershed.

The annual average of SS load were calculated for each monitoring USGS station based on availability of data during the period of 1983 to 2011 (Table 7). Although the USGS stations do not have measured data in exactly the same time periods, they do overlap in their monitoring periods as shown in Figs. 2 and 3. Similarly, annual average rainfall was calculated using data from 1983 to 2011 from rainfall monitoring stations assigned to the study watersheds (Table 7).

The annual average of SS load and concentration were calculated for each monitoring station based on availability of data during the period of 1983 to 2011 (Table 7). Although the USGS stations do not have measured data in exactly the same time periods, they do overlap in their monitoring periods as shown in Figs. 2 and 3. Similarly, annual average of areal rainfall for each watershed was calculated using data from 1983 to 2011 (Table 7).

2.4 Correlation and partial least square analysis

The correlations among the variables were calculated (Proc Corr, SAS® 9.2) to assess the relationship between variables. Correlation analysis was also performed between the precipitation and SS load/concentration to evaluate the impact of precipitation on SS load/concentration for each individual watershed (Table 8). PLS was used to find the association between measured SS load, rainfall and landscape characteristics (e.g., land use type, soil type, and topography). A small sample size, large number of predictors and collinearity between predictors prevented the use of standard multivariate

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regression (Yeniay and Goktas, 2002). However, PLS have been shown to work well under these constraints (Abdi, 2010; Nash and Chaloud, 2002). PLS extracts orthogonal factors (latent variables) requiring that these latent variables explain as much of the covariance between the measured response (SS) and the predictors (landscape variables). This is followed by regression of the predictors on the response (Helland, 1988; Höskuldsson, 1988). Predictor coefficients (magnitude and direction) from the PLS regression can be used to define the role and influence of the predictor variables on response. The magnitude of the coefficient indicates the weight and degree to which the predictor influenced the response; the direction of the influence is "+" for an increase and "–" for a decrease of the coefficient.

3 Results and discussion

3.1 The relationship of SS load/concentration with precipitation

Temporal variation of SS concentration and SS load were analyzed for each of the study monitoring stations; the highest SS concentration occurred in the year 1989 (Fig. 2) and the highest SS load occurred in the year 1998 (Fig. 3) at monitoring station 8. Hurricanes Hugo (in 1989) and Georges (in 1998) generated serious soil erosion and sediment loss. Hurricanes are Puerto Rico's top weather threat because of the damage they cause (Nagle et al., 1999). Hurricane Georges may also be responsible for the higher SS loads that occurred at monitoring stations 4, 17, 18 and 16 in 1998 and also for the higher SS concentrations at monitoring stations 4, 17, 18 and 16. No monitoring information was available for the year 1989 for monitoring stations 4, 17, 16 and 18. Although SS monitoring started in the year 1986 at monitoring station 18, monitoring information was not available for 1989 due to equipment malfunction caused by the hurricane. As expected, Precipitation was a strong predictor for SS concentration and SS load for most monitoring stations. Precipitation explains 19–94 % variation in SS concentration and 19–83 % variation in SS load (Table 8).

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3.2 Comparison of SS load among different USGS monitoring stations

The watershed monitored by station 8 where the highest SS load occurred (see above) has clay soils with relatively low erodibility (Tables 3 and 4); the watershed has the lowest mean slope (Table 6), and an annual average rainfall of 4506 mm which is substantially lower than the mean (Table 7). All these factors suggest watershed 8 should have a much lower SS load. However, watershed 8 has the highest percentage of developed land (47 %; Table 2), which may have outweighed these other factors (Lenat and Crawford, 1994; Mbonimpa et al., 2014).

The driver for SS load in the watershed of monitoring station 4 (second highest load, Table 7) was not the developed lands in the watershed at only 8 % (Table 2), but likely it was associated with the much steeper slopes (Table 6). This is further borne out by the SS load from the watershed of monitoring station 17 (Fig. 3), which has clay soils with low erodibility (Tables 3 and 4), a low percentage of developed land (4 %), but has the highest mean slope (41 % in Table 6).

The lowest SS load occurred in the watershed at monitoring station 9 (Table 7). The main soil was moderately erodible (Tables 3 and 4), with the highest annual average rainfall (Table 7), and moderately steep slopes (Table 6). However, the watershed had 100 % land cover by evergreen forest (Table 2), which may account for the reduced load. Land cover for watershed of monitoring station 14 also had a high degree of natural cover (70 % evergreen forest and 26 % grassland/herbaceous), and the monitoring station 14 also had a very low SS load (Table 7).

3.3 ANOVA test results

We conducted an ANOVA to examine for differences in SS loads from the various watersheds. The SS loads for watersheds monitored by monitoring stations 5, 10, 12, and 19 were not significantly different (P value < 0.05) from the watershed with monitoring station 18. Thus we included only watershed 18 in further analysis because it had the longest monitoring period. Although Watershed 19's SS load did not significantly differ

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from watershed 18, its SS concentration was significantly different (P value < 0.05), and was also included in the subsequent analysis. SS load from watersheds monitored by stations 1, 2 and 3 were not significantly different (P value < 0.05) from watershed 4 so only watershed 4 was included in further analysis. SS load from 7 was not significantly different from 6, so only 6 was included in the subsequent analysis. SS load from watershed 20 was different from other monitoring stations, but only two years of data were available, and it was not included. Thus, eleven watersheds were included for additional analysis with PLS.

3.4 PLS results

PLS regression coefficients indicated the degree and direction of association for land uses, soil types and slope characteristics (Fig. 4). Of the land use categories, water, developed land, and barren lands have appear to greatly increase SS load (Fig. 4), while land covered by evergreen forests, scrub, grass, and pasture decrease the SS load. Water appears to be the strongest predictor of SS loading, however, this may be an artifact of the analysis. Only watershed 8 has water as land use (1 %), and it has the highest developed land use. The rest of the watersheds have no water as a land use. Thus, water as a land use may not be a strong predictor for SS load, and the high regression coefficient associated with it in watershed 8 may be due to the high degree of developed land in the watershed.

Slope can also have a strong and directional influence on SS loading (Fig. 4). For watersheds with relatively low developed land (Table 2), the highest sediment loads come from watersheds 4 and 17 (Table 7). Both these watersheds have very high mean % slope associated with them (Table 6) which may be responsible for higher SS loads (Table 7). The lack of steep slopes may also reduce the amount of SS loading, such as in watershed 11 (Table 7). Generally, soil loss is linearly related to the sine of slope angle for slopes ranging from 9 to 55 % (Liu et al., 1994).

The higher the erodibility of a soil, the higher the potential for increased sediment loading. For example, the major soil type of s9542 (Pellejas-Lirios) in watershed 4 has an erodibility coefficient of 0.17 which could increase SS load (Fig. 4). Soil erosive potential rises as soil particle size content larger than 0.05 mm increases, since the material is less cohesive (Morgan, 2001).

Watershed 15 had a high SS load (Table 7), but it also received the highest rainfall (Table 7). On the other hand, watershed 13 received the same amount of rainfall had the lowest SS load of any of the watersheds. Even with the increased rainfall, other factors associated with land use and soil type may have reduced the SS loading. Watershed 13 has 100 % evergreen forest land cover (Table 2), as well as the majority of soil (s9540, Tables 3 and 4), having low erodibility. It may be that high forested land cover and soil that is not easily erodible in a watershed can reduce SS load even in high rainfall areas. However, neither of these watersheds had a weather station located in them, and the same weather station was assigned to both watersheds based on Thiessen Polygon. This weather station is closer to monitoring station 15 than to monitoring station 13. Thus we cannot rule out that the rainfall data collected at the weather station did not represent the actual rainfall occurring on either watershed.

Subsequent additional regression analysis was used to examine watersheds with high vegetation cover group (< 10 % developed and barren land) and low vegetation cover (> 10 % developed and barren Land) (Table 2). Precipitation has less of an impact on SS load in the highly vegetated watersheds. The slope of the regression for the highly vegetated lands suggests that vegetative cover can retard soil loss, while watersheds with reduced vegetative cover appear to have increased soil loss.

PLS analysis was not efficient in identifying key factors associated with sediment loading from the study watersheds. This was likely due to the complex attributes of these watersheds that often acted in concert, in opposition or in both directions simultaneously to affect the SS loading from the watersheds. However, land use was identified as a strong predictor for sediment loss from the study watersheds, and land use is a factor in these watersheds that can be managed. Vegetation can be an important factor affecting soil erosion processes, and often in areas with serious soil erosion and sediment loss, the natural vegetation has been destroyed (Gyssels et al., 2005;

Shi and Shao, 2000; Zhou et al., 2008). Natural vegetative cover may be able to compensate for the erosive potential of high precipitation and steep slopes (e.g., watershed 13, Table 7). Thus, where development must occur in PR, care should be taken to avoid areas with highly erodible soils, steep slopes and high precipitation.

4 Conclusions

Development was the one controllable factor associated with SS load and SS concentration increases in the study watersheds in PR. These SS loads were also influenced by precipitation, steep terrain and soils with higher erodibility. In watersheds with high percentages of natural vegetative cover (evergreen forest), SS loading was low even in steep terrain with high precipitation. We found PLS unsuccessful in identifying main factors associated with SS loading, because of the complexity of the study watersheds. Future studies are needed to examine the spatial distribution of different land cover types within a watershed in reducing, or mitigating, the SS loads from these complex watersheds.

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Table 1. Independent USGS monitoring stations, the size of the monitored watershed and the time period for available flow and sediment data.

USGS monitoring station ID	USGS monitoring station number	Watershed drainage area (ha)	Flow		Sediment	
			Start	End	Start	End
1	50020500	3289.3	2001	2006	2001	2005
2	50021030	1779.3	2001	2006	2001	2005
3	50022810	774.4	2002	2006	2002	2005
4	50026025	9836.8	1996	2013	1996	2005
5	50035000	33151.9	1947	2013	2003	2007
6	50043800	30514.7	1992	2013	1990	2004
7	50047560	2154.9	1992	2004	1992	2000
8	50048770	1939.9	1991	2008	1989	2003
9	50055000	23258.1	1961	2013	1984	2004
10	50055225	4299.4	1992	2013	1992	2001
11	50055750	5775.7	1991	2013	1991	2004
12	50061800	2548.6	1968	2013	1995	2001
13	50065500	1781.9	1968	2013	1993	2003
14	50071000	3859.1	1962	2013	1996	2004
15	50075000	326.3	1980	2013	1995	2001
16	50110900	3677.8	1990	2013	1990	2004
17	50114900	1882.9	1998	2013	1998	2004
18	50136400	4739.7	1986	2013	1986	2012
19	50145395	1919.2	2004	2013	2004	2006
20	50148890	24501.3	1999	2013	2002	2003

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Table 2. Land use distribution (in percent of total watershed drainage area).

USGS monitoring station ID	Open water	Developed	Barren land	Evergreen forest	Scrub/ Shrub	Grassland/ Herbaceous	Pasture/ Hay
4	0	8	0	65	1	26	0
6	0	13	0	43	6	37	1
8	1	47	2	30	0	20	0
9	0	15	1	36	1	44	3
11	0	8	0	36	1	24	31
13	0	0	0	100	0	0	0
14	0	1	0	70	2	26	1
15	0	0	0	100	0	0	0
16	0	2	0	49	7	42	0
17	0	4	3	71	2	20	0
18	0	2	0	85	2	11	0

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Table 3. Soil type distribution (in percent of total watershed drainage area).

	Soil Type (% of total area)																			
USGS monitoring station ID	s9538	s9537	s9542	s9532	s9539	s9533	s9536	s8369	s9531	s9535	s9553	s9530	s9541	s9543	s9518	s9540	s9552	s9529	s9534	s9544
4	0.1	23	70.9	5.9	0.1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
6	1	–	–	–	8.9	61.2	12.6	0.4	1	9.1	5.8	–	–	–	–	–	–	–	–	–
8	–	–	–	–	–	80.7	19.3	–	–	–	–	–	–	–	–	–	–	–	–	–
9	–	–	–	–	7	25.5	18	–	–	0	13	0.1	1.7	34.7	–	–	–	–	–	–
11	–	–	–	–	–	–	–	–	–	1.2	–	28.3	1.6	–	5.4	29.4	34.1	–	–	–
13	–	–	–	–	–	–	–	–	–	2.4	–	–	–	–	–	97.6	–	–	–	–
14	–	–	–	–	–	–	–	–	–	23.8	–	30	–	–	18.1	28.1	–	–	–	–
15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	100	–	–	–	–
16	38.6	–	–	–	8.3	0.3	–	–	52.8	–	–	–	–	–	–	–	–	–	–	–
17	43	0.2	–	–	–	–	–	56.8	–	–	–	–	–	–	–	–	–	–	–	–
18	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	16.2	81.7	2.1

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Table 4. Soil types and their erodibility, texture and hydraulic conductivity.

SSURGO Code	Soil Name	Erodibility coefficient (USLE_K)	Texture	Ksat (mm h^{-1})
s8369	Water			
s9518	Urban land-Toa-Coloso-Bajura	0.24	Silty clay loam	1.4–4.2
s9529	Rock outcrop-Mucara-Malaya-Caguabo	0.1	Clay	4.2–14.1
s9530	Sabana-Naranjito-Mucara-Caguabo	0.24	Silty clay loam	4.2–14.1
s9531	Quebrada-Mucara-Morado-Caguabo	0.17	Gravelly clay loam	4.2–14.1
s9532	Mucara-Morado-Maraguez-Caguabo	0.1	Clay	4.2–14.1
s9533	Mucara-Caguabo	0.1	Clay	4.2–14.1
s9534	Humatas-Consumo	0.02	Clay	4.2–14.1
s9535	Los Guineos-Lirios-Humatas	0.1	Silty clay loam	4.2–14.1
s9536	Naranjito-Humatas-Consumo	0.1	Clay	4.2–14.1
s9537	Los Guineos-Humatas	0.1	Clay	4.2–14.1
s9538	Maricao-Los Guineos-Humatas	0.1	Clay	4.2–14.1
s9539	Maricao-Los Guineos	0.1	Clay	4.2–14.1
s9540	Utuado-Rock outcrop-Los Guineos- Guayabota	0.17	Silty clay loam	4.2–14.1
s9541	Vieques-Rock outcrop-Pandura	0.17	Loam	4.2–14.1
s9542	Pellejas-Lirios	0.17	Clay loam	4.2–14.1
s9543	Pandura-Lirios	0.17	Sandy loam	4.2–14.1
s9544	Rosario-Nipe-Guanajibo	0.1	Clay	4.2–14.1
s9552	Rio Arriba-Mabi-Dumps-Cayagua-Candelero	0.17	Clay	1.4–4.2
s9553	Urban land-Rio Arriba-Mabi	0.17	Clay	1.4–4.2

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Table 5. Major soil series and their drainage properties.

Name of soil series	Description
Caguabo series	shallow, well drained, moderately permeable soils on side slopes of strongly dissected uplands
Consumo series	very deep, moderately well drained, moderately permeable soils on summits and side slopes of mountains
Guayabota series	very deep, somewhat poorly drained, slowly permeable soils on side slopes of mountains
Humatas series	very deep, well drained, moderately slowly permeable soils on side slopes and ridges of strongly dissected uplands
Lirios series	very deep, well drained, moderately permeable soils formed in materials weathered from Plutonic age which are steep to very steep soils on side slopes and ridge tops of strongly dissected uplands
Los guineos series	very deep, well drained soils on side slopes of mountains
Mabi series	very deep, somewhat poorly drained, slowly permeable soils on alluvial fans and terraces of the Humid Coastal Plains
Maricao series	very deep, well drained, moderately permeable soils on summits and side slopes of mountains
Mucara series	moderately deep, well drained, moderately permeable soils on summits and side slopes of hills and mountains
Naranjito series	moderately deep, well drained, moderately permeable soils formed in material weathered from volcanic rocks which are moderately steep to very steep soils on side slopes and ridge tops of dissected uplands
Pandura series	shallow, well drained soils formed in materials weathered from plutonic rocks which are moderately steep to very steep soils on side slopes of dissected uplands
Pellejas series	very deep, somewhat excessively drained, rapidly permeable soils on side slopes and narrow ridges
Utuado series	very deep, somewhat poorly drained, moderately rapid permeable soils on middle and lower side slopes of strongly dissected uplands

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Table 6. Slope distribution (in percent of total watershed drainage area).

USGS monitoring station ID	Mean slope (%)	Minimum slope (%)	Maximum slope (%)	< 9 %	9–25 %	25–60 %	60–80 %	> 80 %
4	36.4	0.0	166.4	5.3	24.6	58.1	9.5	2.5
6	28.5	0.0	172.0	12.3	34.3	48.7	4.0	0.7
8	14.8	0.0	59.6	22.0	53.0	25.0	0.0	0.0
9	23.4	0.0	134.1	18.7	38.8	41.0	1.4	0.1
11	20.9	0.0	122.4	34.2	27.0	33.3	5.4	0.1
13	37.3	0.5	154.1	1.2	20.9	69.8	7.0	1.1
14	29.8	0.0	126.2	14.4	30.6	47.9	6.3	0.8
15	24.2	0.5	70.4	11.4	41.9	41.5	5.2	0.0
16	37.0	0.0	157.3	2.9	24.0	63.0	8.1	2.0
17	41.0	0.0	111.7	1.8	15.3	69.9	11.3	1.7
18	33.5	0.0	104.9	3.8	26.3	64.6	5.0	0.3

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Table 7. Annual average rainfall and sediment load for each monitoring station.

USGS monitoring station ID	Annual Average Rainfall in mm (1983 to 2011)	Annual Average Sediment Load in $t\,ha^{-1}$ (1983 to 2011)
4	5550	25.4
6	4294	9.9
8	4506	56.1
9	5322	9.4
11	4964	5.6
13	10360	2.8
14	7232	8.3
15	10360	21.3
16	3462	8.1
17	4335	22.0
18	5972	8.5

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Table 8. Rainfall and SS load/concentration correlation coefficients

USGS monitoring station ID	Coefficient of rainfall and SS load	Coefficient of rainfall and SS concentrations
4	0.49	0.53
6	0.78	0.77
8	0.19	0.19
9	0.57	0.55
11	0.83	0.94
13	0.30	0.67
14	0.53	0.50
15	0.73	0.80
16	0.57	0.71
17	0.24	0.79
18	0.38	0.36

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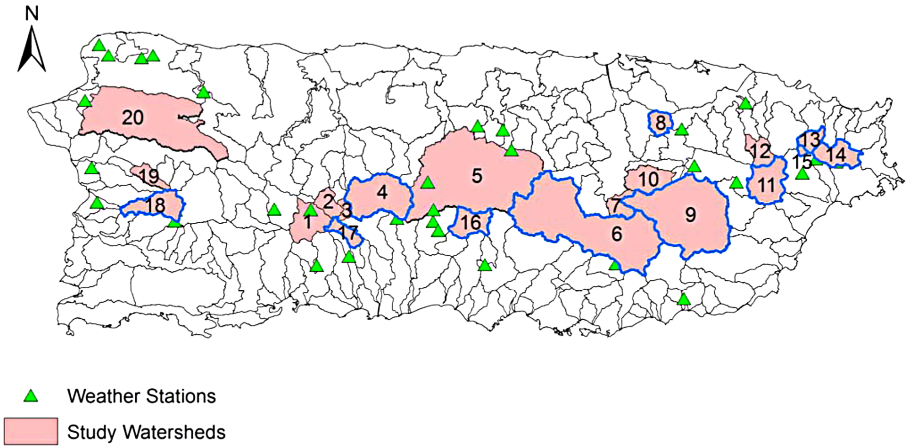

Figure 1. Puerto Rico's NOAA weather stations (green triangles). Color filled watersheds were for the study. Those watersheds with the blue outline were used for PLS analysis. The number within the watershed refers to the USGS monitoring station number in Table 1.

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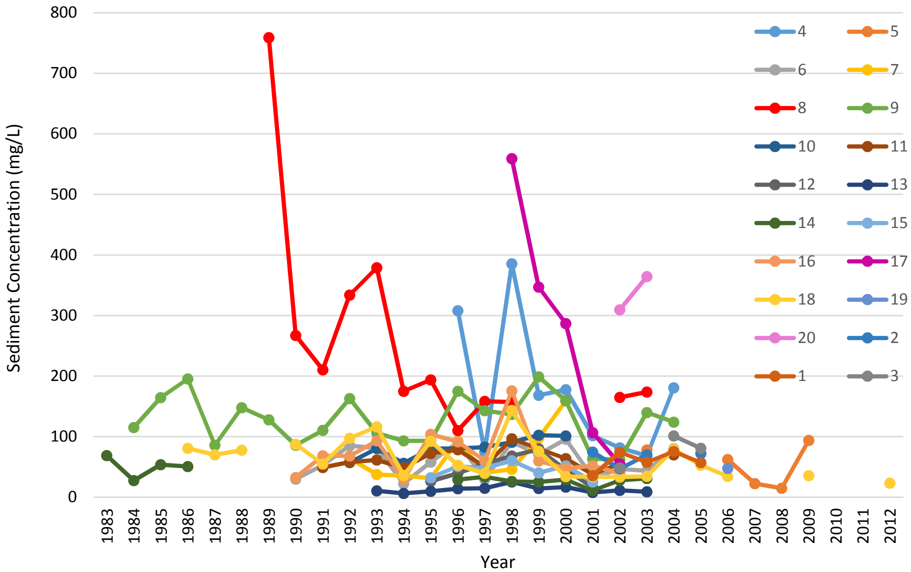

Figure 2. Comparison of suspended sediment concentration (mg L^{-1}) from different monitoring stations.

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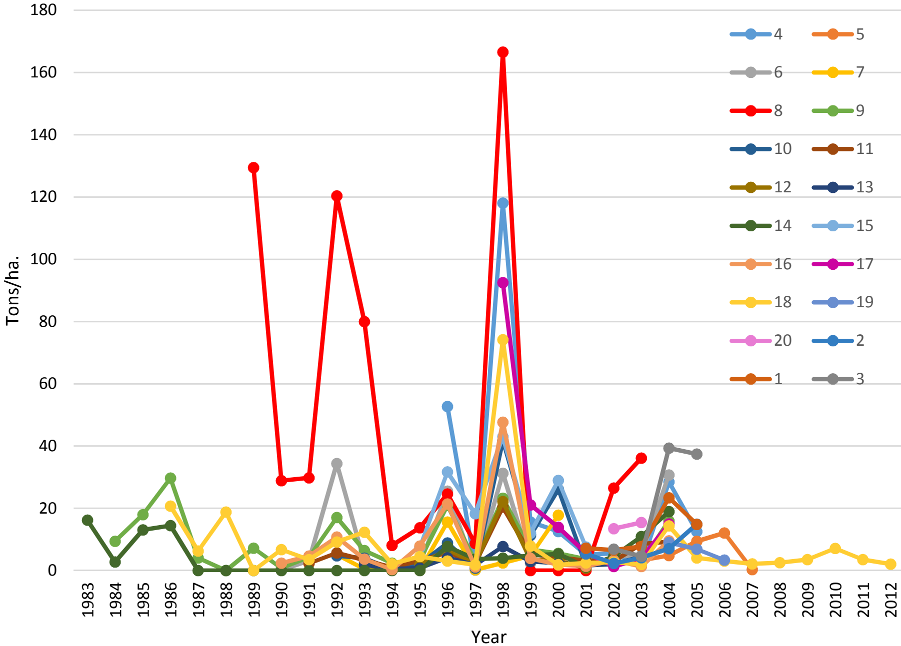

Figure 3. Comparison of suspended sediment load ($t\,ha^{-1}$) from different monitoring stations.

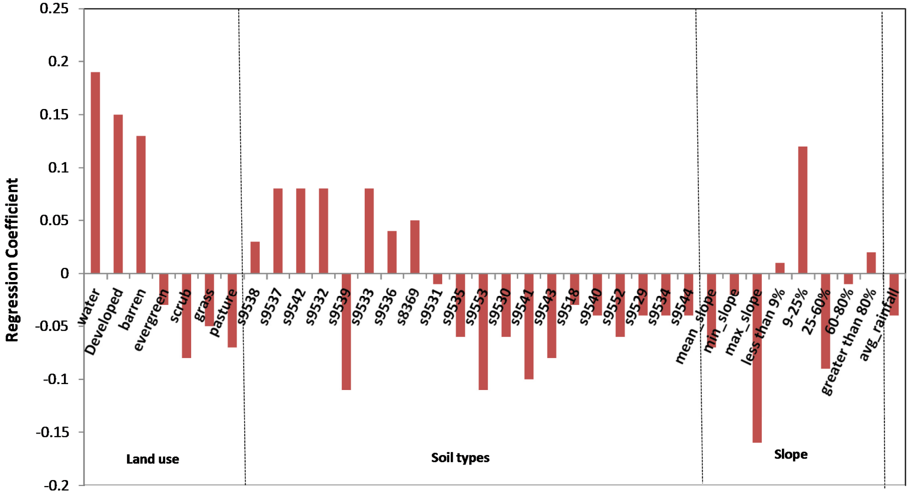

Figure 4. PLS regression coefficients of each predictor on SS load.

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