QUANTIFYING SEDIMENT CONTRIBUTIONS TO THE GUÁNICA BAY PUERTO RICO

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ABSTRACT

Puerto Rico faces considerable challenges regarding sustainable land use and effects of land use on adjacent freshwater and marine ecosystem services. In watersheds feeding Guánica Bay (southwestern Puerto Rico), increased soil erosion and sediment loading to streams has raised concern that sediment has reduced reservoir capacity, polluted the Bay, and adversely affected coral reef condition in the coastal zone. The success of potential management options will depend partly on knowing where the sediment originates and what factors contributed to sediment losses. However, the hydrology in the region is very complex. Guánica Bay is fed almost exclusively by Rio Loco, but waters in Rio Loco come from as many as six different watersheds, a consequence of five reservoirs constructed in the early 1950s that are linked by tunnels. In addition, water from the lowest of these reservoirs, Lago Loco, is distributed by gravity far to the west (Lajas Valley) for agricultural irrigation and returned by drainage canal to Rio Loco before it empties into Guánica Bay. Increased sediment loading may result from increased agricultural production in the region since the 1950's, especially the growth of sun-grown coffee plantations along mountain ridges. The overall objectives of our research are to: 1) quantify sediment contributions from upstream watersheds to Rio Loco; 2) identify sediment sources and factors which contributed high sediment losses; and 3) explore alternative strategies to reduce soil erosion and sediment loading to the reservoirs, Guánica Bay and the coastal zone. This presentation describes two aspects of the ongoing research: (1) application of the Soil and Water Assessment Tool (SWAT) to ridge watersheds, where coffee is grown, to estimate soil erosion and sediment loading to the reservoir, and (2) application of Gridded Surface Subsurface Hydrology Analysis (GSSHA) to estimate water flow and sediment transport in the Lucchetti watershed, which receives water and sediment from three ridge watersheds through underground tunnel. Preliminary modeling results by SWAT and GSSHA are presented.

ENVIRONMENTAL ISSUE

Terrestrial sediment entering the coastal zone has been identified as one of the stresses adversely affecting coral condition on reefs outside of Guánica Bay (Warne et al., 2005). High intensity rainfalls, steep slopes and agricultural activities have caused significant soil erosion and landslides which have increased sediment loadings to the waterbodies in the Guánica Bay Watershed. Sediment loading has also caused turbidity in streams, rivers and reservoirs and has dramatically reduced the storage capacity of reservoirs that supply water for irrigation, electricity generation and domestic use. A survey of reservoirs in Puerto Rico found losses of 12% to 85% of water storage capacity because of sediment loading (Soler-Lopez 2001). The storage loss of reservoirs in southwestern Puerto Rico, such as Lago Lucchetti, also threatens downstream areas that are prone to flooding (GLM, 2009). Human activities such as clearing land for agriculture and road and residential construction may accelerate soil erosion and sediment transport. There is an urgent need to identify sediment sources and factors affecting soil erosion and sediment transport. Likewise, there is a need to develop methods that allow the continued high agricultural productivity of these hilly mountainous areas while reducing soil losses and sediment transport to surface waters.

RESEARCH GOAL

This research aims to:

1. Quantify soil erosion and sediment contributions from upstream watersheds;
2. Identify sediment sources for different waterbodies in the region;
3. Characterize the influence of agricultural practices on soil erosion and sediment transport; and
4. Evaluate alternative strategies to reduce soil erosion and sediment loading to the reservoirs, Guánica Bay and the coastal zone.

METHODS AND PROCEDURES

The Study Area and Data Collection

The Guánica Bay watershed is located in the southwestern corner of Puerto Rico (Figure 1). The entire watershed is about 387 km² and includes an urbanized area (Yauco), Lajas Valley agricultural region, and the upper mountainous watersheds where coffee farming and subsistence agriculture are practiced on steep and often highly erodible lands. Five reservoirs were constructed in the 1950's ranging from the upper mountainous watersheds to the southern foothills: Lago Yahuecas, Lago Guayo, Lago Prieto, Lago Lucchetti, and Lago Loco (Fig. 1). A SWAT model was used to estimate water flow and sediment transport into Lago Yahuecas, a mountain reservoir. Since the US Geological Survey (USGS) gauge at the Yahuecas watershed (38.9 km²) has only streamflow data, sediment data from the adjacent USGS gauge in Adjuntas watershed (48.4 km²) were used for SWAT model calibration and validation. Elevations in the two watersheds range from 370 to 1200 m with steep slopes of 25% to 60% occupying 60 percent of the watershed. Annual precipitation is about 2000 mm, and the maximum and minimum temperatures were 34.4 and -0.6 °C from 1970 to 2012. The major land use is forest, coffee and (forage) grass which accounts for about 60%, 20 % and 10% of the watershed area, respectively. A GSSHA model was used to estimate the water flow and sediment transport into Lago Lucchetti, which receives contributions from the Lucchetti watershed as well as from upper watersheds through tunnels. Lucchetti watershed is dominated with forest and grass which covers 65.7% and 28.6% of the area, respectively. Other land uses include shrub (3.3%), water (1.7%), and developed (0.7%). Elevations in Lucchetti watershed range from 160 m 960 m with steep slopes. Clay, clay loam, and silty clay loam are the three major soil texture types in all three watersheds.

Fig.1: Study area

Table 1: Various data collected for model input, model calibration and validation.

Data	Source	Date	Description
DEM	National Elevation Data (NED)	2001	30m*30m resolution, USGS
Soil	Soil Survey Geographic Database (SSURGO)	2012	Digital representation of County Soil Survey maps, USDA-NRCS
Land Use	National Land Cover Database	2001	30m*30m resolution, USGS NLCD
Weather	Daily precipitation and temperature (TMIN/TMAX) from NOAA station (660061 and 660053)	1946 - present	NOAA NCDC
Weather	Hourly wind speed, barometric pressure, sky cover, temperature and relative humidity (PENUELAS station 998249)	1996-2005	US Air force
Streamflow (GSSHA)	Daily data from Rio Yauco at Lucchetti Dam site (USGS 50125790)	1945-1952	USGS Gage
Streamflow (SWAT)	Yearly and monthly flow from USGS gages (50014100 and 50020500)	1981 – 1984 2001 – 2004	USGS Gage
Sediment (GSSHA)	Sediment of bathymetric surveys	2001	USGS 2001 bathymetric surveys
Sediment (SWAT)	Yearly and monthly data for SS obtained from USGS gage (50020500)	2001 – 2004	USGS Gage

GSSHA Model

The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model developed by the US Army Corps of Engineers (USACE) is a physically-based, distributed hydrologic model, used for single events or long term simulation. Process calculations are summarized in table below (Downer and Ogden 2004, 2006):

Process	Method
Infiltration	Green and Ampt with Redistribution (GAR)
Overland flow routing	Alternative Direction Explicit (ADE)
Channel routing	1D diffusive wave-up-gradient Explicit
Evapotranspiration	Penman-Monteith
Lateral groundwater flow	2-D vertically averaged
Stream/groundwater interaction	Darcy's law
Overland erosion	Modified Kilinc-Richardson equation
Sediment Routing	Unit stream power

The GSSHA and SWAT models, when combined with other models for the Guánica Bay/Rio Loco system, will help to quantify and identify sources of sediment and evaluate potential management actions to reduce delivery of sediment to Guanica Bay and the coastal coral reefs.

SWAT Model

The Soil and Water Assessment Tool (Arnold et al., 1998; Arnold and Fohrer, 2005; Gassman et al., 2007) have been developed to aid in the evaluation of watershed response to agricultural management practices. Conservation practices are evaluated through a continuous simulation of runoff, sediment and pollutant losses from watersheds. In Soil and Water Assessment Tool (SWAT), a watershed is divided into multiple subwatersheds, which are further subdivided into Hydrologic Response Units (HRUs) that consist of homogeneous land use, management, and soil characteristics. Flow generation, sediment yield, and non-point-source loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Modified SCS-CN, Green-Ampt, and Mein-Larson equations are used in SWAT model to simulate runoff, and MUSLE (Modified Universal Soil Loss Equation) is used for calculating sediment yield in each HRU (Neitsch et al., 2009).

RESULTS AND DISCUSSION

GSSHA Model

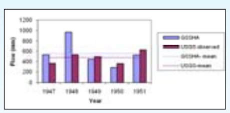

Fig. 2: Comparison of simulated (GSSHA) and observed (USGS) flow: There was 14 % prediction error which could be attributed to missing weather records and errors in model parameter estimation.

SITE	USGS code	Water Yield (mm)	Total SuspendedSolid (ton/ha/mo)
Rio Yauco	50025850	90.8	0.59
Rio Pellejas	50021030	122.1	0.62
Rio Grande near Adjuntas	50020500	141.6	1.12
Rio Grande near Utuado	50021700	90.0	1.08
Rio Vivi	50022810	107.7	1.94
Lago Prieto	N/A	N/A	0.75
Lago Guayo	N/A	N/A	0.71
Lago Loco	N/A	N/A	1.50
Lucchetti	Lucchetti	78.0	2.65

Table 2: Comparison of GSSHA simulated water and sediment yield at Lucchetti reservoir with monitored water and sediment yield at nearby USGS monitoring sites. The Lucchetti reservoir received the highest sediment loading, which was due to a combination of steep slopes, soils with low hydraulic conductivity and high precipitation.

Fig.3: Lucchetti and USGS monitoring sites

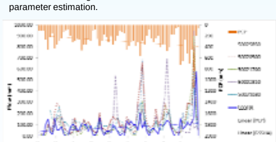

Fig.4: Comparison of monthly flow (2000-2005), showing an increase in flow from 2000 to 2005 from increased precipitation. The difference in large event peaks could be attributed to high spatial variability in precipitation, common during hurricanes.

Fig.5: Comparison of monthly sediment (2000-2005). Although Lucchetti did not have the highest flow, it had the highest sediment, which means slope and soil properties could be the main differences between the other watersheds and the Lucchetti watershed.

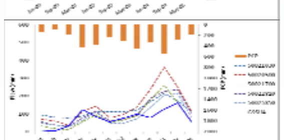

Fig.6: Monthly average flow (2000-2005). The period between September and November experienced the highest flows.

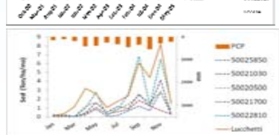

Fig.7: Monthly average sediment (2000-2005). Sediment peaks are observed in April, September and November due to high precipitation.

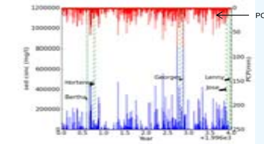

Fig.8: Sediment concentrations associated with large events such as hurricanes and tropical storms (1996-1999). Hurricane Georges was associated to the highest precipitation and sediment concentration in streams between 1996-1999. This graph shows that this tropical area experienced many extreme erosive events

Sun to shade-grown coffee		
Year	Flow	Erosion
1996	-2.2	-24.8
1997	-1.1	-24.1
1998	-0.8	-21.8
1999	-0.4	-22.2
Average	-1.1	-23.2

Table 3: Flow and erosion changes due to conversion from sun to shade-grown coffee. There is an average of 23.2 % reduction in sediment from converting sun to shade grown-coffee. Trees grown to provide shade for coffee protect soil from erosion.

Fig.9: Spots with high erosion in the watershed and channel sediment concentration during a rainfall event (01/13/1996: 8:00 PM).

Depressions on hills are more prone to sediment loss and landslides due to steep slopes. Also sediment concentration in stream increases as you move downstream.

SWAT Model

Table 4 : Model performance on monthly flow at Yahuecas and Adjuntas

Statistics	Yahuecas				Adjuntas	
	Calibration period (1981-1982)		Validation period (1983-1984)		Simulation period (2001-2004)	
	Observed flow (m³/s)	Simulated flow (m³/s)	Observed flow (m³/s)	Simulated flow (m³/s)	Observed flow (m³/s)	Simulated flow (m³/s)
Mean	1.01	0.97	0.98	1.14	1.66	1.27
R^2	0.90		0.90		0.64	
NSE	0.84		0.86		0.59	
RME	0.04		-0.16		0.23	

Table 5: Model performance on sediment at Adjuntas

Period	Year	Annual average sediment concentration			Model performance on monthly sediment concentration (mg/L)		
		Observed (mg/L)	Simulated (mg/L)	*RE* (%)	R^2	*NSE*	*RME*
Calibration Period	2001	44.2	40.54	-8.28	0.15	-0.02	0.15
	2002	77.8	34.83	-55.23			
Validation Period	2003	71.1	51.7	-27.29	0.32	0.27	0.38
	2004	59.8	58.91	-1.49			

SWAT underestimated annual average sediment concentration of 2001 to 2004, and this may be due to that SWAT model does not simulate landslide and gully erosion happened in the watershed.

Table 6: Observed Precipitation and simulated sediment loss in rainy season at Adjuntas

Year	Precipitation (mm)			Simulated sediment loss (Ton)		
	Rainy season Feb. to May, Aug. to Nov.	Annual total	Percentage of rainy season to annual total (%)	Rainy season Feb. to May, Aug. to Nov.	Annual total	Percentage of rainy season to annual total (%)
2001	1188.3	1566.3	76	1068.1	1429.6	75
2002	1232.0	912.5	74	1118.3	1583.7	71
2003	1614.8	1941. 8	83	5198.3	5970.7	87
2004	1692.0	2291.2	74	2648.8	3673.6	72
Mean	1431.8	1677.9	77	2508.4	3164.4	76

Rainy seasons (February-May and August -November) contributed 76% of annual sediment loss as predicted by SWAT model.

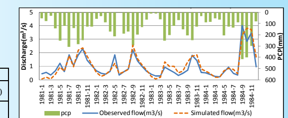

Fig.10: Comparison of simulated and observed monthly flow at Yahuecas (1981-1984). The simulated flow matched the observed very well. The highest flows occurred in months of April, May, September and October which were caused by high rainfalls in those months.

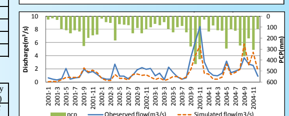

Fig.11: Comparison of simulated and observed monthly flow at Adjuntas (2001-2004). The SWAT model underestimated the stream flow in Adjuntas because the observed stream flow was unreasonably high compared to precipitation.

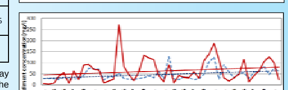

Fig.12: Comparison of simulated and observed monthly sediment concentrations at Adjuntas (2001-2004). The SWAT model underestimated the monthly sediment concentration, especially for months with high sediment. Sediment concentration increases from 2001 to 2004.

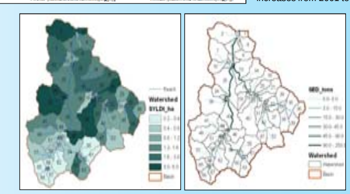

Fig.13: Annual sediment export (Tons ha^{-1} yr^{-1}) in the sub-basins and sediment (Tons yr^{-1}) in the channels of Adjuntas (2001-2004) predicted by SWAT. The highest sediment export was in subbasin 24 which is 6 Ton/ha/yr (380 Tons/yr.); and the highest sediment in the channel was in reach 5 (234 Tons/yr.)

CONCLUSIONS

- The Lucchetti watershed erosion rate is one of the highest in the region with 2.65 Tons/ha/mo. Likewise, Lucchetti reservoir receives the highest sediment loading (Soler-Lopez , 2001).
- Conversion of sun-grown coffee to shade-grown coffee in the region could reduce erosion significantly, including a 23 % reduction in the Lucchetti watershed.
- In Yahuecas watershed, the highest flows occurred in months of April, May, September and October,which were attributed to peaks in monthly rainfall.
- In Adjuntas watershed, rainy seasons (February-May and August -November) contributed 76 % of annual sediment loss as predicted by SWAT model.
- In Lucchetti and Adjuntas, a linear fit to monthly sediment load shows that sediment load increased from 2000-2005 and 2001-2004, respectively.
- In Adjuntas, the highest sediment loss from the landscape was 380 tons/yr (6 tons/ha/yr) and the highest erosion from channels was 234 tons/yr. Sediment in streams increased in downstream reaches.

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