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The Effect of Land Use on Soil Erosion in the Guadiana Watershed in Puerto Rico

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ABSTRACT.—The Revised Universal Soil Loss Equation (RUSLE) was used in conjunction with a Geographic Information System to determine the influence of land use and other environmental factors on soil erosion in the Guadiana watershed in Puerto Rico. Mean annual erosion, suspended sediment discharge, and the rainfall-erosion factor of the RUSLE increased with annual rainfall. Median soil erosion rates varied among the seven land uses: bare soil (534 Mg $ha^{-1}yr^{-1}$), open canopy forest (26 Mg $ha^{-1}yr^{-1}$), agriculture (22 Mg $ha^{-1}yr^{-1}$), pasture (17 Mg $ha^{-1}yr^{-1}$), less dense urban (15 Mg $ha^{-1}yr^{-1}$), closed canopy forest (7 Mg $ha^{-1}yr^{-1}$), and dense urban (1 Mg $ha^{-1}yr^{-1}$). The differences between open canopy forest, agriculture, pasture, and less dense urban were not significantly different but median values for open canopy forests were slightly greater because they occurred on steep slopes. The five-year average sediment delivery ratio for the basin was 0.17, which is comparable to delivery ratios estimated for watersheds of similar size. Simulations of different land use configurations indicate that reforestation of 5% of the watershed with the highest erosion rates would decrease basin wide erosion by 20%. If the entire watershed was reforested, soil erosion would be reduced by 37%.

RESUMEN.—Se utilizó la versión revisada de la Ecuación Universal de Pérdida de Suelo (RUSLE, según sus siglas en ingles), en conjunto con Sistemas de Información Geográfica, para determinar la influencia del uso del terreno y otros factores ambientales sobre la erosión del suelo en la cuenca hidrográfica del Río Guadiana en Puerto Rico. La erosión promedio anual, la descarga de sedimento suspendido y el factor lluvia-erosión de RUSLE aumentaron según aumentó la precipitación anual. Se encontró una variación entre las medianas de las tasas de pérdida de suelo respecto a las siete clases de uso de terreno: suelo expuesto (534 Mg ha^{-1} $año^{-1}$), bosque de dosel abierto (26 Mg ha^{-1} $año^{-1}$), agricultura (22 Mg ha^{-1} $año^{-1}$), pastizal (17 Mg ha^{-1} $año^{-1}$), urbano menos denso (15 Mg ha^{-1} $año^{-1}$), bosque de dosel cerrado (7 Mg ha^{-1} $año^{-1}$) y urbano denso (1 Mg ha^{-1} $año^{-1}$). No se encontró diferencia significativa entre el bosque de dosel abierto, agricultura, pastizales y urbano menos denso, pero los valores de las medianas del bosque de dosel abierto fueron mayores porque este uso de terreno ocurre en pendientes más escarpadas. El promedio para los cinco años de estudio de la razón de sedimento que llega al río fue 0.17, el cual es comparable con la razón estimada para cuencas hidrográficas de igual tamaño. Simulaciones diferentes de uso de terreno indican que reforestar el 5% de las áreas de la cuenca donde la erosión es mayor disminuiría la erosión en la cuenca en un 20%. Si se reforestara la cuenca por completo, la erosión del suelo disminuiría en un 37%.

INTRODUCTION

Soil erosion is a natural and inevitable process that can become a serious environmental and economic problem when it is accelerated by human activities. Water supplies and storage reservoirs, freshwater and coastal environments, agricultural and urban productivity can all be negatively impacted by accelerated soil erosion. While the importance of minimizing soil erosion is widely recognized, determining the spatial distribution of erosion is a necessary prerequisite to developing erosion management plans for specific areas. The purpose of this study was to use a Geographic Information System (GIS) to integrate digital data of soils, land use, and topography to estimate the spatial distribution of soil erosion in the Guadiana watershed of Puerto Rico. This watershed is located in the north-central region of Puerto Rico (Fig. 1)

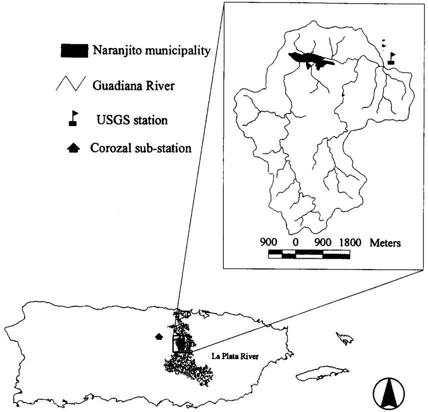

FIG. 1. Location of the study area within La Plata basin of Puerto Rico. The USGS Station is located at the point where the Guadiana River enters La Plata reservoir.

and is a major tributary of the La Plata reservoir. This reservoir supplies water to approximately 36% of the San Juan metropolitan population but has lost nearly 30% of its storage capacity to sediment since it was built in 1974 (Díaz et al., 1995).

Soil erosion and transport is a complex process that is influenced by soil type, topography, climate, and land use. In areas where soil, climate, and topography are similar, differences in erosion rates are commonly related to land use. For example, in Malaysia, the rate of soil erosion increased from 0.24 t ha^{-1} yr^{-1} under natural forest to 4.9 t ha^{-1} yr^{-1} in areas of mature coffee, to 7.32 t ha^{-1} yr^{-1} in areas with cultivated vegetable crops (Shallow, 1956 as cited in Lal, 1990). In Puerto Rico, soil erosion in coffee plantations without ground cover was ten times greater than from adjacent areas of coffee with natural ground cover (Smith and Abruña, 1955) and in Trinidad erosion rates were higher for bare soil than for cropped lands (Gumbs and Lindsay, 1982). In general, any land use that reduces vegetation cover increases soil erosion.

Land use practices in Puerto Rico have changed dramatically during the last century (Dietz, 1989; García-Montiel and Scatena, 1994; Thomlinson et al., 1996). During the peak of the agricultural era (1930-1950) less than 5% of the island was forested (Birdsey and Weaver, 1987; Thomlinson et al., 1996). Since that time the island's economy has shifted to an industrial based economy. Consequently, there has been a decrease in agricultural lands and increases in the area of secondary forest, urban lands, and construction sites. While the net effect has been a reduction in soil erosion on the island (Zack and Larsen, 1993; Clark, 1997), erosion and sedimentation of water supply reservoirs are major environmental problems.

METHODS

The Guadiana watershed occurs within the subtropical moist forest life zone (Ewel and Whitmore, 1973) and has a drainage area of 23.8 km^2. Mean annual precipitation at the nearest NOAA meteorological station (Corozal station, 14 km northwest of the watershed) for the 49 years of record (1930-1959, 1964-1995) was 1910 mm. Mean annual precipitation for the period covered in this study (1991 to 1995) was 1619 mm (Table 1). During the study period the U.S. Geological Survey (USGS) collected suspended sediment discharge data at the point where the Rio Guadiana enters the La Plata reservoir (Fig. 1).

Soil erosion and sediment yields were estimated for the years 1991 to 1995 using the Revised Universal Soil Loss Equation (RUSLE) (Wischmeier, 1976):

$$A = R * K * L * S * C * P$$

where: A is the soil erosion calculated in English tons/acre/year; R = rainfall factor; K = soil erodibility factor; L = slope length factor; S = slope steepness factor; C = cover and management factor; and P = erosion control practice factor. The K and R factors are dimensional and expressed in terms of tons/acre/yr. The L, S, C, and P factors are dimensionless. Our results were converted to Mg/ha/yr.

The rainfall factor (R) and the erodibility factors (K) used in this study were taken from the most recent National Resource Conservation Service RUSLE guidelines for Puerto Rico (US- NRCS, 1995). In the analysis of mean annual erosion, an R value of 400 was used in accordance with the NRCS iso-erosivity map of Puerto Rico. In a separate analysis comparing soil erosion between years, an R value was calculated for each year of the study (Table 1). These annual values were estimated from an empirical relationship between average annual precipitation (1981-1995) and the R factor from the iso-erosivity map for 11 meteorological stations from different regions of Puerto Rico (Fig. 2).

Erodibility (K), length (L), and slope (S) factors of the RUSLE were both polygon and soil series specific. The soil polygon coverage of the watershed was based on the standard soil series map of the area (Boccheciamp, 1978). The K values and descriptions of each soil series within the watershed are included in Table 2. The L and S factors for each soil series polygon were calculated using topographic information

TABLE 1. Precipitation, R value, soil erosion, suspended sediment discharge, and calculed sediment delivery ratios (SDR) during the study.

Year	Mean precipitation (mm)[1]	R value	Soil erosion ($Mg\ yr^{-1}$)	Suspended sediment discharge ($Mg\ yr^{-1}$)[2]	SDR
1991	1511	386	83846	10283	0.12
1992	1843	474	102961	34137	0.33
1993	1625	417	90580	16303	0.17
1994	1049	265	57562	1592	0.03
1995	2066	532	115559	25928	0.22
Average	1619	415	90102	17649	0.17

[1]Data from NOAA, 1995
[2]Data from Diaz et al., 1991-1995

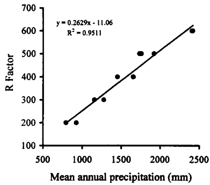

FIG. 2. Relation between average annual precipitation for 14 years and R factor for 11 meteorological stations in Puerto Rico.

from USGS Digitial Line Graphs (DLG) and a 30 m grid Digital Elevation Model (DEM) derived from the DLG. To account for the variation within each polygon we used an average of five random measurements for the L factor and ten for the S factor.

The cover and management factors (C) for this analysis (Table 3) were determined from island wide values (i.e., Table 4 in US-NRCS 1995a), field observations, and aerial photographs. Black and white aerial photographs from 1995 were used to create a GIS land use cover of the watershed. Each polygon on these photographs greater than 50 × 50 m was assigned to one of seven land use classes (Table 3). The C factor for each land use class was determined using standard island values (i.e., Table 4a in NRCS 1995). Field observations indicated that most of the agriculture in the basin was plantains. Therefore a C value of 0.05 was used for all agriculture areas. Since field observations also indicated that erosion management practices are not used within the watershed, the erosion control practice factor (P) was set to 1.0 for all land uses.

Geographic data was analyzed using PC Arc/Info version 3.4.2b (ESRI, 1994) and ArcView version 3.0 (ESRI, 1996). The GIS digital data included the watershed boundary, hydrography, land use for 1995, topography, and soils. All of these coverages were mapped at a scale of 1:20,000 and transformed to the Lambert coordinate system for Puerto Rico. A GIS cover of the watershed was then created for the K, LS, and C factors of the RUSLE equation. These three coverages and the R-value for each year were multiplied to generate an annual soil erosion cover (Table 1). These yearly totals were compared with USGS suspended sediment discharge data (Díaz et al., 1991 to 1995) and an annual sediment delivery ratio (SDR) was calculated by dividing the annual suspended sediment discharge by the annual soil erosion.

To evaluate the effects of different land uses on soil erosion in the basin, the erosion

TABLE 2. Soil series distribution showing percent cover in the Guadiana watershed, K factor attributed to each soil series[1], and a general description of each soil series[2].

Soil series	% cover	K Factor	Description
Mucara	43.2	0.10	Clay, moderately deep, well drained
Consumo	16.3	0.10	Clay, deep, well drained
Naranjito	14.7	0.10	Silty clay-loam, moderately deep, well drained
Pellejas	7.9	0.17	Clay loam, deep, well drained
Maricao	7.4	0.10	Clay, deep, well drained
Caguabo	3.6	0.24	Clay loam, shallow, well drained
Humatas	3.6	0.02	Clay, deep, well drained
Aibonito	1.2	0.02	Clay, deep, well drained
Mucara (Urban)	1.2	0.10	Clay, moderately deep, well drained
Lirios	0.4	0.10	Silty clay-loam, deep, well drained
Río Arriba	0.3	0.17	Clay, deep, moderately drained
Aceitunas	0.1	0.02	Clay, deep, well drained
Cartagena	0.1	0.24	Silty clay-loam, deep, poorly drained

[1]Data from NRCS, 1995a
[2]Description from Boccheciamp, 1978

TABLE 3. Land use classes used in the aerial photograph classification. The C Factor was based on information in NRCS (1995a).

Land use class	Photo characteristic	C Factor	% cover
Closed canopy forest	Coarse texture, more than 80% tree cover	0.014	56.9
Open canopy forest	Coarse texture, 25-80% tree cover	0.023	14.5
Pasture	Smooth texture, up to 25% tree cover	0.032	16.6
Agriculture	Uniform texture, furrows	0.05	0.3
Less dense urban	Scattered buildings within areas of pasture or forest	0.02	9.4
Dense urban	Town, high density of buildings	0.001	1.7
Bare soil	Areas without any cover	1.00	0.6

from different combinations of land cover was calculated. In all of these simulations, only the cover and management factor (C) for different areas and land uses was changed. Moreover, the rainfall factor R (R = 400), the amount of areas in urban land uses, and the K, LS and P factors for individual polygons, remained constant for each simulation.

RESULTS

Aerial photographs indicated that in 1995 closed canopy forest (57%) was the dominant land use in the Guadiana watershed (Table 3; Fig. 3). Pastures (17%) and open canopy forest (15%) were also prominent land uses. Most of the forested area occurred in the northern part of the watershed and most of the pastures occurred in the southern region. Only 0.3% of the watershed was in agriculture. The town of Naranjito was the largest contiguous area classified as dense urban. Small, dispersed communities (e.g. less dense urban class) accounted for 9% of the study area. Approximately 0.6% of the watershed was devoid of vegetation (i.e. bare soil). These bare areas were typically less than 5.0 ha in area. The largest contiguous area of bare soil was the construction site of a new road.

Slopes within the watershed vary from gradual (0-10%) to a steep (>45%) (Fig. 3). The steepest slopes within the watershed occur to the south of the main channel of the Guadiana river. The relatively flat areas occur in the southern part of the watershed and to the north of the Guadiana river. Nearly 40% of both forest classes occurred on the steepest slopes, while less than 3% occurred on the gentlest slopes (Fig. 4). Although some pasture (19%) occurred on steep slopes (>45%), 80% of the pastures were located on slopes with inclinations between 15 to 45%. Agricultural areas had a similar relationship with slope, as pastures with most of the agriculture occurred on intermediate slopes (15-45%). Of all the land use types, urban areas had the greatest percentage on the most gentle slopes (Fig. 4). Areas of bare soil were concentrated on intermediate and steep slopes.

Thirteen soil series occur within the Guadiana watershed (Table 2, Fig. 3). However, most of the watershed (74%) is dominated by three soil series (Mucara, Consumo, and Naranjito). Forested areas were typically underlain by the Mucara and Naranjito soil

TABLE 4. A comparison of average slope and rates of soil erosion (t $ha^{-1}yr^{-1}$) in different land uses categories from different studies in Puerto Rico.

Site	Slope (%)	Forest	Pasture	Agriculture	Bare soil	Reference
Lake Carraizo	43	7.4	46.9	244.4	162.9	US-NRCS, 1995b
Mayaguez	NA	NA	2.6	39.7	339.7	Smith and Abruña, 1955
Guadiana River	40	7.5	17.1	22.1	534.1	Present study[1]
Guadiana River	40	13.4	36.0	56.8	459.6	Present study[2]

[1]medium values of polygons expressed in Mg $ha^{-1}yr^{-1}$
[2]averages values of polygons expressed in Mg $ha^{-1}yr^{-1}$

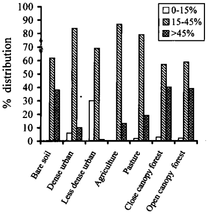

FIG. 4. Land-use distribution relative to different slope categories.

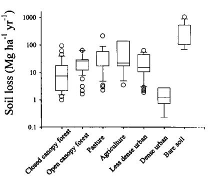

FIG. 5. Boxplots showing soil erosion in the different categories of land use. The line within the box represents the median, the box represents the middle half of the data, the vertical lines represent the range of typical values, and the circles represent outliers.

and was part of a road construction project. This construction was also on the Caguabo soil series, the most erodible soil in the watershed. In the center of the watershed there were two other areas with relatively high erosion rates (>46 Mg ha^{-1} yr^{-1}). These areas occurred on Mucara soils and contained a mixture of open canopy forest and pastures land uses (Fig. 3). The steep slopes in these areas were a major factor contributing to their high rates of soil erosion.

Soil erosion also varied among and within each land use (Fig. 3 and Fig. 5). Erosion was greatest in areas of bare soil (median 534 Mg ha^{-1} yr^{-1}) and lowest in dense urban areas (1Mg ha^{-1} yr^{-1}). The median rate of soil erosion was slightly higher in the open canopy forest (26 Mg ha^{-1} yr^{-1}) compared to pastures (17 Mg ha^{-1} yr^{-1}), agriculture (22 Mg ha^{-1} yr^{-1}), or less dense urban (15 Mg ha^{-1} yr^{-1}). However, the differences between these four land uses were not significantly different (Kruskal Wallis-Pairwise comparison of mean ranks, P >0.05). With the exception of the dense urban class, areas classified as closed canopy forest had the lowest median erosion rate (7.5 Mg ha^{-1} yr^{-1}). However, erosion rates from polygons with closed canopy forest varied from 1Mg ha^{-1} yr^{-1} to 92.6 Mg ha^{-1} yr^{-1}.

There was a significant positive relationship between the annual RUSLE estimate of basin wide soil erosion and measured suspended sediment discharge (R^2 = 0.78, P <0.1; Table 1, Fig. 6). In the year of lowest rainfall, 1994, soil erosion and suspended sediment discharge were the lowest. The year of highest rainfall, 1995, had the second highest suspended sediment discharge. The sediment delivery ratio for the study period averaged 0.17 (Table 1). The

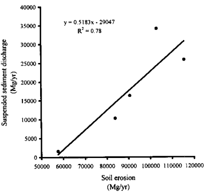

FIG. 6. Relationship between soil erosion estimated by RUSLE and suspended sediment discharge data reported by USGS.

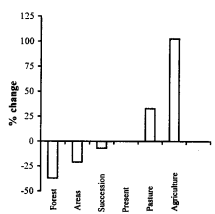

FIG. 7. Different scenarios of land use and the percent change of soil erosion. "Forest", "Pasture", and "Agriculture" represent the entire watershed covered by closed canopy forest, pasture, or agriculture, respectively. Areas classified as "urban" in the 1995 aerial photographs were left as urban in these simulations. "Succession" implies the conversion of areas covered by open canopy forest to closed canopy forest with other uses remaining the same. "Areas" represents reforestation in those areas of the watershed where soil erosion exceed 46 Mg ha^{-1} yr^{-1}. "Present" is the actual condition of the watershed.

standard empirical relationship between SDR and drainage basin area (US-SCS, 1983) indicates that a basin the size of the Guadiana should have a SDR of 0.18.

Simulations indicated that changes in land use cover within the watershed could have greatly affected soil erosion (Fig. 7). Moreover, if land use in all non-urban areas of the watershed was entirely pastures or agriculture, soil erosion would increase 33% and 103%, respectively. In contrast, if the entire watershed was reforested to closed canopy, soil erosion would be reduced by 37%. The model also predicts that when open canopy forest succeeds to closed canopy forest, soil erosion will be reduced by 7%. If all areas currently in agriculture, pastures, and bare soil that have erosion rates greater than 46 Mg ha^{-1} yr^{-1} (5% of the watershed) were converted to open canopy forest, there would be a 20% decrease in soil erosion.

DISCUSSION

Soil erosion within the Guadiana watershed varies spatially and temporally. In general, soil erosion increases with annual rainfall, slope, and land uses with open canopies. The comparison of estimated soil erosion within the Guadiana watershed, with suspended sediment discharge at the basin outlet, indicates that on average 17% of eroded soil reaches the watershed outlet as suspended sediment (i.e. SDR = 0.17, Table 1). This SDR is comparable to that estimated for basins of similar size elsewhere (US-SCS, 1983) and indicates that 83% of eroded sediment is deposited before it reached the basin outlet. Most of this sediment is probably deposited at the base of hillslopes or on flood plains before it reaches the stream channel.

The median rate of soil erosion in polygons of different land uses decreased in the following pattern: bare soil > open canopy forest > agriculture > pastures > less dense urban > closed canopy forest > dense urban. However, median annual erosion rates between areas of open canopy forest, pasture, agriculture, and less dense urban were not significantly different. With the exception of the relatively high erosion rates in areas of open canopy forest, this pattern is similar to those found in other watershed studies (Lal, 1990) and in plot measurements of erosion made in Puerto Rico (Smith and Abruña, 1955). The relatively high erosion rates estimated for areas with open canopy forest sites is related to the topographic conditions where open canopy forests occur (Fig. 4). Moreover, although greater vegetative cover in the open forest protects the soil from the direct impact of precipitation, the steep, long slopes result in greater soil erosion compared to areas with active agriculture and pasture on more gentle slopes. Because agricultural areas that are abandoned first are typically on steeper slopes, this pattern of relatively high erosion rates under open canopy forests may be common in other areas undergoing similar land use changes.

The estimated rates of soil erosion in the present study are higher than those reported for similar land uses in temperate zones, but are within the range reported for humid tropical areas (Lal, 1990; Clark, 1997). With the exception of agricultural and barren areas, the median values of soil erosion reported here are similar to those of a RUSLE based study of the Carraizo watershed in NE Puerto Rico (US-NRCS, 1995b; Table 4). Although the slopes and rainfall in the two watersheds were similar, the RUSLE estimates of agricultural erosion are higher in the Carraizo watershed, while estimates from bare soil are higher in the Guadiana watershed. Part of the difference is related to the fact that a large proportion of the barren areas in the Guadiana watershed was on some of the most erodible soils in the island. In addition, much of the agriculture in the Carraizo basin is characterized by annual row crops on steep slopes rather than plantains on gentle slopes as in the Guadiana watershed. Because plantains are perennial, grow to 3 to 4 m in height, and have large leaves, they apparently protect the soil better than annual row crops which have barren areas for extended periods.

In addition, the Guadiana and Carraizo studies integrated data at different spatial scales. The Carraizo watershed (536 km^2) was divided into six units, while the Guadiana watershed (23.8 km^2) was divided into 523 units. By calculating soil erosion at a smaller scale, we are more confident that the individual parameters have been correctly assigned for each unit. Soil erosion based on plot measurements in Mayaguez (Smith and Abruña, 1955) also showed the same trends (erosion in pastures < agriculture < bare soils) as in the Guadiana watershed, giving additional support to the estimates made in the present study.

The simulations of soil erosion in the Guadiana watershed with different configurations of land use suggest the range of soil erosion that may have occurred in the past and may be occurring now. If the entire watershed was covered by a closed canopy forest, as it was during pre-European times, soil erosion would be 37% of its present value. In contrast, during the first half of this century when most of the watershed was in agriculture, soil erosion may have been 103% greater than it is presently and nearly 3 times that or pre-European rates. Estimates of historic changes in soil loss in Northeastern Puerto Rico also indicate that during the agriculture era soil erosion loss could have been almost 5 times that of pre-European times (Clark, 1997).

Comparisons of watershed-scale erosion under different land use configurations also indicate that one of the most effective ways to reduce soil erosion in this watershed is to reforest the areas of highest soil erosion (>46 Mg $ha^{-1} yr^{-1}$). These sites, which comprise 5% of the watershed, are mainly areas of bare soil and pasture or agriculture on steep slopes. By reforesting these areas to open canopy forest, soil erosion within the watershed would be reduced by 20%. If all pasture and agriculture were eliminated and reforested to closed canopy forest, 17% of the watershed would have to be reforested and soil erosion would be reduced by 37%. While the social costs and benefits of different land use configurations must be considered separately, these observations demonstrate the need to have spatially explicit information on soil erosion. They also confirm that the combined use of the RUSLE and GIS is an effective method for estimating watershed scale soil erosion and evaluating the effectiveness of various management practices.

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