

Mass Wasting and Sediment Storage in a Small Montane Watershed: an Extreme Case of Anthropogenic Disturbance in the Humid Tropics

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By the peak of land-use conversion for subsistence cropping and plantation agriculture in Puerto Rico in the 1940's, 94 percent of the original forest cover had been eliminated. In a small (26.4 km²) upland watershed that typifies this land-use history, field surveys and examination of aerial photographs indicate that more than 2,000 landslides have occurred since about 1820 when forest clearing began. The landslides are attributable to a combination of three factors: a highly weathered bedrock (Cretaceous granodiorite), episodic heavy rainfall, and almost two centuries of intense land-use practices. On average, landslide scars number 140/km² in the Cayaguás watershed, equal to 80 landslide scars/km²/100 y. The volume of hillslope material eroded by landsliding is estimated at 660,000 m³/km² (870,000 Mg/km²). If all colluvium was transported from the catchment, then the volume is equivalent to a mean surface lowering of the entire watershed by 660 mm, or 3.8 mm/y. Soil augering, field observations at construction sites, road cuts and stream banks, mapping from aerial photographs, and GIS-based estimates of the surface area of footslopes, indicate that colluvium may total 149,000 Mg/km². If mobilized, this would be sufficient stored material to supply the annual average fluvial sediment yield for as long as 129 years. The great availability of colluvial and alluvial sediment on footslopes, floodplains, and in channels will maintain high sediment yield well into the 21st century in spite of government efforts to reforest hillslopes and institute other hillslope soil conservation measures.

INTRODUCTION

Understanding the processes and the rates by which land surfaces are altered by natural and human geomorphic agents is a central focus of geomorphological research and a fundamental requirement for effective management of natural resources. In environments that have undergone or are undergoing rapid land-surface alteration for agriculture, construction, or logging, case studies and conceptual geomorphic models enable land managers to attempt to mitigate landscape degradation. This information base can assist planners in other similar settings to predict outcomes of development strategies.

Researchers working in many settings have quantified the sources, as well as the routes and rates of movement of detrital material through a drainage basin to evaluate watershed status and sustainability and to interpret landform change [Caine and Swanson, 1989; Dietrich and Dunne, 1978; Graf, 1987; Kelsey, 1980; Kelsey et al., 1987; Madej and Ozaki, 1996; Montgomery et al., 2000; Phillips, 1986; Sutherland and Bryan, 1991]. The common approach is to determine annual fluxes of hillslope and fluvial sediment and make estimates of residence time of sediment that is in storage between these two [Costa, 1975; Jacobson and Coleman, 1986; Meade, 1982; Trimble, 1981]. Although these types of studies must use estimates of the quantity and spatial distribution of stored sediment, they provide valuable insight into the geomorphic behavior of a catchment.

The important role of stored colluvial and alluvial sediment with respect to fluvial sediment yield has been documented in temperate and subtropical environments. The stored material, derived from anthropogenic or natural sources, e.g. glaciation, can maintain higher than predisturbance sediment yields well after the initial disturbance is complete [Haggett, 1961; Costa, 1975; Trimble, 1977; Meade, 1982; Church and Slaymaker, 1989]. Sustained high sediment yields may degrade water quality, reservoir capacity, and estuarine and near-shore marine environments until stored sediment is immobilized or exported, and an equilibrium land-use practice is achieved.

Landsliding triggered by earthquakes or rainfall is the dominant process of hillslope erosion in many montane humid tropical environments [Garwood et al., 1979; Jones, 1973; Larsen et al., 1999; Maharaj, 1993; Reading et al., 1995; Scatena, 1995; Simonett, 1967]. Rainfall during intense and (or) prolonged storms has been the principal cause of landslides in Puerto Rico during the 20th century [Larsen and Simon, 1993; Larsen and Torres-Sánchez, 1998]. Because of relatively short distances to channels in upland watersheds, hillslope material eroded by landslides is commonly delivered directly to stream channels resulting in high sediment delivery ratios [Ahmad et al., 1993; Gupta, 1988; 1995; Larsen and Parks, 1997]. If hillslope angles are low or footslopes and floodplains are wide enough, some of the colluvium may reside in temporary storage before being entrained by fluvial processes. It is this buffer area of sediment storage that, because of its great spatial and temporal variability, confounds much of the research on hillslope erosion and fluvial transport of sediment.

Long-term data sets of hillslope erosion and fluvial sediment transport are difficult and expensive to develop. As a consequence, relatively few definitive studies exist, particularly in tropical environments. Because of extensive Federal and

Commonwealth government-sponsored data collection programs, Puerto Rico serves as a data-rich natural laboratory for such studies. A large network of surface-water gaging stations, automatic water samplers, and rainfall gages is operated by the U.S. Geological Survey [USGS, 1999]. In addition, regular aerial photographic surveys have been conducted and land cover has been quantified for a number of years during the 20th century.

These data sets provide an opportunity to address several research questions in a small, montane catchment in Puerto Rico: How much hillslope soil has been eroded by mass wasting, principally by landsliding, at what rate has erosion occurred, and what has been the effect of anthropogenic disturbance in this process? How much sediment is sequestered on footslopes and in and near river channels, and finally, what is the rate of fluvial export of sediment from this watershed?

CAYAGUAS WATERSHED DESCRIPTION

The Cayaguás watershed (26.4 km²) is in southeastern Puerto Rico, about 35 km south of San Juan (Fig. 1). The watershed drains to the north and is bordered on the south by the Cayey Mountains. The climate is humid tropical with a mean annual rainfall of 1,930 mm and a mean annual temperature of 25°C [U.S. Department of Commerce, 1999]. Hillslopes are steep in the watershed; the mean slope is 19% (10.8°) and total relief is 293 m (Table 1). The average (map) channel gradient of the Cayaguás river is 12% (6.8°). The Cayaguás watershed is a tributary to the Río Grande de Loíza, which has the largest drainage basin in Puerto Rico, and flows into the Loíza Reservoir (Fig. 1). Constructed in 1953, this 267-ha impoundment supplies about 50% of public water to the 1.6 million inhabitants of metropolitan San Juan. Bathymetric surveys completed in 1994 indicate that sediment infilling of the reservoir, discussed below, had eliminated 47% of the original capacity [Webb and Soler-López, 1997].

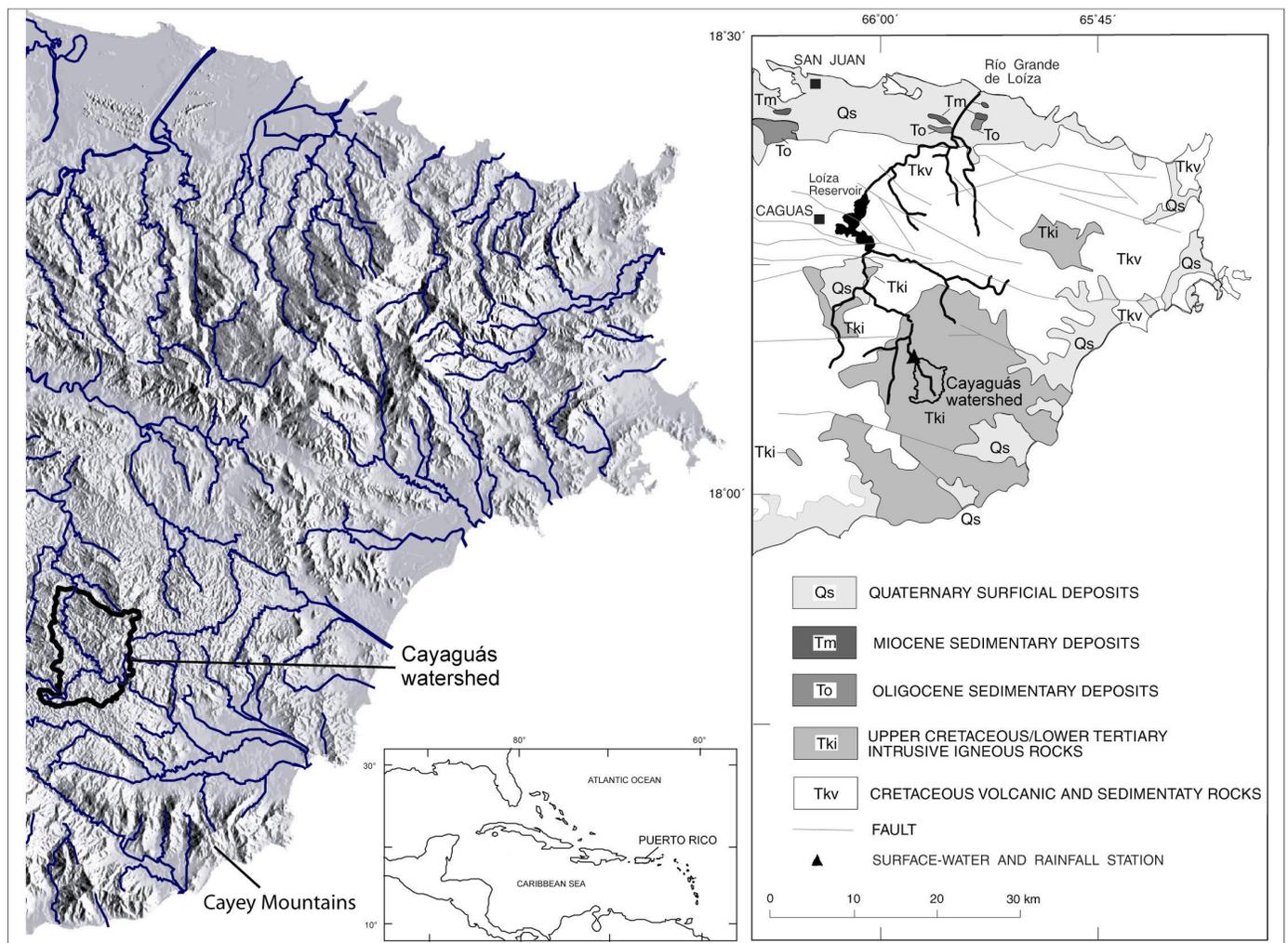


Figure 1. Shaded relief and simplified geology of eastern Puerto Rico showing location of the Cayaguás watershed (geology modified from Monroe, 1980).

Table 1. Geomorphic, geographic, and streamflow characteristics for the Cayaguás watershed [U.S. Geological Survey, 1999].

Mean annual runoff, 1975 to 1995, mm	1480
Mean annual rainfall, mm	1930
Watershed drainage area, km ²	26.4
Stream order at surface water gaging station, Strahler	5
Total watershed relief, m	293
Mean slope of watershed, dimensionless	0.19
Mean channel slope, dimensionless	0.12
Main channel (5th order) length, km	10.1
Total channel length, km	172
Drainage density, km/km ²	6.5

The Upper Cretaceous Granodiorite of San Lorenzo, a batholith which occupies a 500-km² area of southeastern Puerto Rico, underlies 88% of the Cayaguás watershed [Broedel, 1961; Rogers *et al.*, 1979]. The granodiorite is medium to dark gray, medium-grained, and contains 51% plagioclase, 21% quartz, 11% each of potassium feldspar and hornblende, and 5% biotite. About 11% of the southeastern part of the Cayaguás watershed was mapped as quartz monzonite. This rock type ranges locally in composition to a granodiorite, but the median composition is 35% plagioclase, 33% quartz, 28% potassium feldspar and 2% each hornblende and biotite. The remaining 1% of the watershed is mapped as Quaternary alluvium, described as clay to boulder-sized material, including remnants of low terraces, and having a thickness of more than 10 m locally.

The high rate of chemical weathering of the crystalline granodiorite bedrock produces abundant material for transport due to the highly erodible nature of intrusive rock in this humid tropical watershed. As feldspars are weathered during the year-round wet and warm environment, the rock matrix disaggregates and weathers to saprolite at depth and to an easily transported *grus* (medium- to coarse-grained sand) visible at the soil surface [Gerrard, 1994]. Judging from saprolite thickness in nearby undisturbed forest in the same bedrock type, saprolite may have had a pre-forest clearing thickness of several meters or more on ridgetops and hillslopes [Simon *et al.*, 1990; Larsen, 1997]. The thick layer of saprolite and regolith have provided abundant material for landsliding.

Landslide basal surfaces vary with rainfall intensity: short-duration, high-intensity storms frequently mobilize only a few 10's of cm of regolith above the saprolite surface; long-duration storms with deeper infiltration of rainwater may induce landslides that fail at the weathered rock-saprolite boundary [Larsen and Simon, 1993; Larsen, 1997].

Although large corestones are abundant on many hillslopes and in some channel reaches, most material delivered to drainage channels is sand sized ($D_{50} = 0.6$ mm)[Larsen, 1997]. Consequently, fluvial erosion and transport has been efficient at the millennial to geologic time scale, enhancing channel extension, as manifested by high drainage density seen on topographic maps of the area (Table 1). Modern evidence can be seen in active slumping at the heads of tributaries of some zero-order valleys. In addition to extension, widening of main channel valleys results from mass wasting on valley sides. Headward extension of these has enabled the stream system to approach within 12 km of the south (Caribbean) coast of the island, in spite of being part of a north coast draining river that crosses a straight-line distance of more than 50 km to reach the Atlantic Ocean (Fig. 1).

Ultisols (Tropohumults, Tropodults) and Inceptisols (Eutropepts) are the dominant soil orders in the Cayaguás watershed, typical of the upland areas of Puerto Rico [U.S. Department of Agriculture, 1977]. Alfisols (Tropaqualfs) are mapped along some valley floors. Hillslope soils are predominately sandy clay loam. Soil erosion by *slopewash* has been estimated to be 10 Mg/km²/y at sites in secondary forest (15° mean slope angle) and in pasture (24° mean slope angle) in the Río Grande de Loíza watershed, which includes the Cayaguás watershed [Gellis *et al.*, 1999]. In addition, Gellis *et al.* [1999] reported that *slopewash* ranges from 31 to 86 Mg/km²/y on hillslopes with active agriculture (16° mean slope angle). In a *slopewash* erosion study in undisturbed forest in the Luquillo Experimental Forest, a preserve administered by the U.S. Forest Service, in eastern Puerto Rico, Larsen *et al.* [1999] estimated erosion rates of 46 Mg/km²/y on steep hillslopes (41° mean slope angle) underlain by intrusive bedrock, comparable to the bedrock in the Cayaguás watershed. Soil creep is estimated to contribute 11 Mg/km²/y to stream channels [Larsen, 1997; Lewis, 1974]. Gullying was observed on steep sections of unpaved roads, on areas of cropland, and on landslides scars in the Cayaguás watershed. However, the frequency and the magnitude of observed gullies does not indicate that gullying is an important agent of hillslope erosion in this watershed [Gellis *et al.*, 1999; Larsen, 1997].

Specific 19th-century land-use data for the Cayaguás watershed are limited. It can be assumed that land-use history until the 20th century was generally comparable to island-wide averages (Fig. 2). According to Morales-Muñoz [1943], settlers migrated up the Río Grande de Loíza valley from San Juan as early as the 16th century. Cattle were introduced to roam the unfenced forest, and were periodically rounded up for consumption or sale in San Juan. A large tract of land (about 100 km²) that extended from the present-day city of Caguas southeast to the Cayey Mountains, and included all of the Cayaguás watershed, was ceded by the Spanish crown to Miguel Muñoz de Oneca *ca.* 1700. The land remained in the Muñoz de Oneca family for most of the following century and agricultural

development was limited until the early 19th century. During the 19th and early 20th centuries, common agricultural practices included the use of alternating cash (tobacco and sugar cane) and subsistence (beans, corn, roots) crops [Beishlag, 1955]. Individual farm size generally varied with hillslope; areas with gentle slopes had farms averaging 10 ha whereas areas with the steepest slopes had farms averaging only 2 ha. Many farms, however, were very small; for example, a government resettlement program in the 1940's installed families on plots of 0.1 to 1 ha [Beishlag, 1955]. The small average plot size on steep slopes meant that areas most vulnerable to soil erosion were likely to be farmed intensively by families whose survival depended on the limited land area. This resulted in a negative feedback mechanism whereby the productivity of the eroded hillslopes declined forcing families to keep the land in constant production (Fig. 3). On numerous small farms in the mountainous interior of the island, decreasing soil fertility resulted in using the land to graze cattle. For example, by mid 20th century, out of 6,059 farms in southern Puerto Rico, 76% had up to 5 head of cattle each. After the 1940's, the amount of land used for agriculture began a marked decline as rural population sought work in Puerto Rico and U.S. industrial centers (Fig. 2). Off-island migration rates were high enough to cause a dip in population growth during the 1950's. A rapid rise in forest cover also occurred, and by the 1970's, the percentage of land in forest was the highest it had been in 100 years.

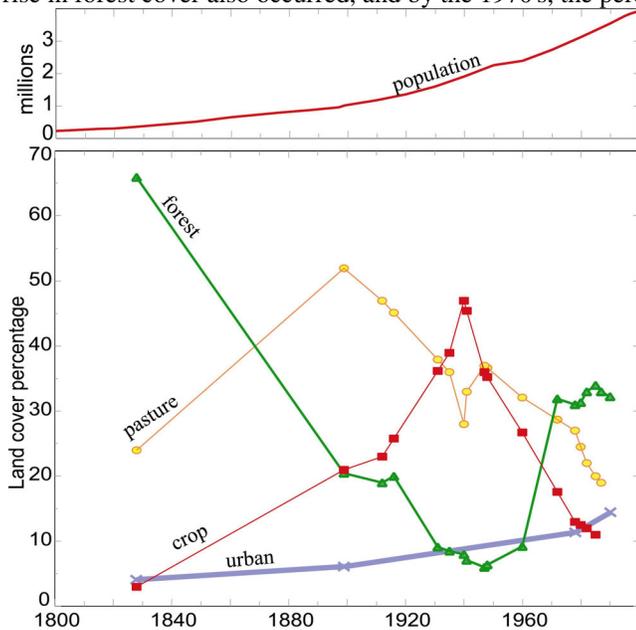


Figure 2. Generalized 19th-20th century land-use classification and population for Puerto Rico (land-use data from Alberts, 1940; Wadsworth, 1950; Birdsey and Weaver, 1987; Franco et al., 1997).



Figure 3 . Rural family and residence, 1940's, eastern Puerto Rico, with deforested hillslopes in background. (Photograph taken by F.H. Wadsworth, International Institute of Tropical Forestry, U.S. Forest Service, Río Piedras, Puerto Rico).

At present, vegetation in the Cayaguás watershed is dominated by actively-grazed pasture and secondary forest. A wide variety of broad-leaf tropical evergreen trees is present. The principal crop species are *Colocasia esculenta*, (known locally as malanga) also known as taro, grown on wet bottomland soils, *Dioscorea rotundata* (locally known as ñame), which is planted in raised mounds on hillslopes and ridgetops where drainage is good, and *Musa sp.* (plantains, bananas), also planted where drainage is good.

Population statistics for the Cayaguás watershed can be approximated by using U.S. Census data for the municipality of San Lorenzo, within which the watershed is contained. In 1990, population density was 97 inhabitants/km², the annual per capita income was \$2,888, and 72% of the families were below the U.S. government poverty threshold [*U.S. Department of Commerce*, 1991].

METHODS

Landslides and Land use

Stereo pairs of black and white aerial photographs dating from 1937, 1951, and 1995 (scales ranging from 1:17,000 to 1:20,000) were examined with 2- to 4-power magnifying stereo viewers to determine the generalized land-use categories (for 1937 and 1995), and the location and extent of landslide scars. Land-use classification was also derived for 1950 from published maps [*Brockman*, 1952]. Field personnel from the Puerto Rico Agricultural Extension Service and the U.S. Natural Resources Conservation Service were interviewed to determine agriculture practices and history. Although mapping of landslides in the entire watershed was planned at the outset of this study, the extremely high number of landslide scars present resulted in a scaled down approach in which some areas of the watershed were not mapped.

Landslides were classified as recent or historic. Recent scars were defined as those that occurred during the previous 10 years and were observed on aerial photographs with a sharp break or disruption in vegetation type, little to no vegetation regrowth, bare soil or soil with little vegetation regrowth, and other geomorphic characteristics such as a clearly definable steep head and side scarps, hummocky soil and downslope debris deposits [*Larsen and Torres Sánchez*, 1998; *Wieczorek*, 1984]. Because of extensive area in actively-grazed pasture in the watershed, old landslide scars are easily recognized [*Gellis et al.*, 1999]. These 'historic' landslide scars were defined as having occurred approximately within the past 100 years (but possibly dating to the early 1800's) and having some vegetation regrowth, subdued head and side scarp boundaries, and eroded or absent debris deposits. Each landslide was assigned an identification number, and the length (both initiation area and runout) and width were estimated by using a calibrated ruler. Length measurements based on aerial photographs are necessarily shortened in proportion to slope angle. This was corrected by using the cosine function and slope angle determined with geographic information system (GIS) software [*ESRI*, 1993]. An approximate scar depth was estimated by using the typical rural Puerto Rican house height as a gage; 3 m in 1937 and in 1951, and 3 to 6 m in 1995. Using the product of the average soil density and individual landslide volume, an eroded mass was estimated for each scar. This value is affected in many cases by continued erosion of head and side scarps after the initial failure occurrence. These values were summed and divided by the watershed area to normalize the erosion rate. The landslide type was classified according to scar morphology into debris flow, slump, soil slip, debris avalanche, earthflow, and complex, using the terminology of *Cruden and Varnes* [1996] and *Campbell* [1975]. Analysis of aerial photography allows the cataloging of landslide scars in an extensive area; however, the technique is limited by the poor quality of some black and white photographs taken in 1937 and in 1951. During field reconnaissance, landslide scars not visible on aerial photographs were commonly observed where forest canopy and shadows on steep hillslopes mask landslide features. The number of landslides identified in the watershed is therefore presumed to be underestimated.

A total of 203 of the landslides mapped in this study were field checked to evaluate the accuracy of dimensions, classification, and location as determined in the photographs. In addition, soil samples were collected to determine bulk density. Field measurements of landslide length and width were accomplished by using a metric tape or a rangefinder and a stadia rod to measure scar depth. The landslide depths recorded were the average along the scar. Landslide lengths were defined as the distance from head scarp to the slope base. Hillslopes in the Cayaguás watershed are relatively short (10's to ~150 m), and the erosive portion of landslide scars was usually continuous across this distance. Because only accessible, visible scars were chosen for field checking, it is possible that the correspondence between field- and aerial photograph-determined measurements may be poorer than that discussed below. However, landslide scars that are difficult to measure because of forest cover or remoteness would reduce the quality and quantity of field data. This is because scar morphology is difficult to recognize and measure under broadleaf tropical evergreen forest canopy, particularly with the dense understory typical of second-growth forest. Simple linear regression models relate the dimensions of landslides mapped in the field to the dimensions estimated from aerial photographs. The models were used to adjust all the dimensions of landslide scars cataloged from aerial photographs in this study.

Sediment Storage

Sediment resides in various storage compartments in a watershed before it is either entrained by fluvial and mass-wasting processes or sequestered for long time scales. These compartments can be described as active, semiactive, or inactive depending on how potentially mobile the deposits may be [*Madej*, 1995]. In the Cayaguás watershed, channel bars and the channel bed were defined as active, floodplains and colluvium were defined as semiactive, and Quaternary alluvium was defined as inactive.

Perennial stream-channel length is substantially under represented on the 1:20,000-scale USGS topographic maps that cover the study area (maps date from 1960 and 1967). This is the result of several factors. The maps were made from aerial photographs with limited resolution. First-order streams are very narrow and in many cases, are located where forested and shrub-covered hillslopes and shadows obscure them from the view of the map maker. Black and white aerial photographs have an approximate resolution of 5 to 10 m, depending on local variation in photograph quality, magnification, illumination, air quality, and humidity when the photo was taken. As a result, the exact location of first-order stream channels is beneath the resolution of the technology used to make the topographic maps in the 1960's, particularly with respect to the determination of where water is flowing. An expanded hydrographic network was approximated following standard techniques using a digital elevation model (DEM) with a 5 m cell width that was derived from digital 1:20,000-scale topography (Table 1) [*Tarboton et al.*, 1991]. Using an approximate minimum contributing area for first-order perennial streams of 7,500 m², a stream channel network was created. The minimum contributing area was determined by field mapping the

location of perennial flow in first-order channels using a Global Positioning Satellite unit. The contributing area upstream was then measured using GIS software. Although local heterogeneity in such factors as groundwater flow paths, bedrock weathering, and slope results in variable contributing area across a watershed [Montgomery and Dietrich, 1989], this approximation is an improvement over the under-represented perennial stream channel lengths shown in the topographic maps for the Cayaguás watershed. The stream order, total channel length, and drainage density listed in table 1 were derived from the expanded hydrographic network developed with the methodology described above.

Watershed sediment storage was estimated by using field surveys of channel bars and channel width. The length, width, and height of unvegetated channel bars that are subaerial at base flow were measured in three reaches of the Cayaguás River. The bar surface area per length of measured channel was proportioned to Strahler stream order and multiplied by the overall perennial stream-channel length to estimate the total bar surface area [Strahler, 1956]. The bulk density of sediment composing channel bars was measured by collecting volumetric samples, and drying the material at 105°C for 24 hours. The mean bulk density of bar sediment was multiplied by the bar volume to calculate bar mass. GIS software was used to estimate the surface area of floodplains, all river channels, Quaternary alluvium, and footslopes with colluvial storage.

Channel bed sediment volume was quantified by calculating channel area and multiplying by a mean thickness that ranged from 0.02 to 1 meter, ranked by stream order. The bed-thickness value was based on observation of bedrock, coarse gravel, and boulders underlying the channel sand exposed by episodic degradation during the period from 1984 to 1999.

Channel surface area was determined by using the expanded perennial stream-channel length and a sample of measured channel widths at various locations between the basin outlet and headwaters. The areal extent of floodplain alluvium was calculated to a first approximation along all stream channels by using the 5-m DEM with GIS software and the following calculations. First, based on proportions observed in the field during channel bar surveys, a corridor of land having a width double that of the average channel width was created along all stream channels. The average channel width used was that determined from stream order. Next, the surface area with a slope of 4° or less was determined inside of the corridor adjacent to the channels [Larsen, 1997]. Finally, the area of the actual channel was subtracted from the corridor to arrive at the estimate of total floodplain area. Alluvium thickness was estimated by examining exposures on stream channel banks.

The distribution and mass of colluvial deposits is widespread in the watershed on footslopes and near the heads of zero-order basins. No accurate method for estimating this mass exists short of detailed field measurements. The total volume of landslide scars affords an upper-limit estimate of the total amount of colluvium generated if it is assumed that most colluvium postdates the oldest visible scars. This is a reasonable assumption based on observations in a nearby forested watershed with the same bedrock type where little colluvium exists on footslopes [Larsen, 1997; Larsen and Torres Sánchez, 1998]. An alternative approach provides a more conservative estimate of colluvial storage. Using GIS software and the 5-m DEM, a map of hillslopes with slopes of 10° or less was made. The low slope areas on the tops of ridges and saddles were eliminated as no colluvium is deposited in these locations. In addition, all watershed surface area inside the floodplain boundaries was eliminated. The resulting map provides an estimate of the total surface area of colluvial deposits; the surface area then was multiplied by the average thickness of colluvium, as determined by soil augering, and field observations at construction sites, road cuts and stream banks.

Fluvial Sediment and Runoff

Suspended and bed load sediment transport data were compiled from previous USGS studies to summarize annual yield [Guzmán-Ríos, 1989; Larsen, 1997; Simon and Guzmán-Ríos, 1990; USGS, 1999]. Annual runoff data were derived from a USGS data base for a surface-water gaging station, USGS ID 50051310, at the outlet of the Cayaguás watershed [USGS, 1999]. A continuous stage recorder has been maintained at this location since 1977.

RESULTS

Land use

Land-use characterization based on aerial photography indicates that by 1937, pasture was the dominant land cover for 84% of the surface area of the Cayaguás watershed (Fig. 4). Forest cover accounted for 12% of the area and the remainder was in crop and farm houses. Recent work indicates that as cultivated areas are abandoned, the land typically has reverted to pasture [Aide *et al.*, 1995]. This serves as a transitional, or buffer state, as it may be easily returned to cultivation after remaining fallow for several years. Alternatively, if cattle are kept off the land, secondary forest has been shown to recover in similar watersheds in Puerto Rico within about 20 years [Aide *et al.*, 1995]. Land-use practices in the watershed during the latter half of the 20th century diverged from the island average as pasture continued to be the primary land use at 66% of land cover in the Cayaguás watershed in 1995. This compares to pasture land cover of less than 19% for the island overall in 1987 (Fig. 2). During the second half of the 20th century, cropped areas decreased while forest cover and clusters of rural housing increased. Forest cover in 1937 was about 12% and decreased to less than 5% by 1950 [Brockman, 1952]. Forest recovery to 23% of the Cayaguás watershed had occurred by 1995.

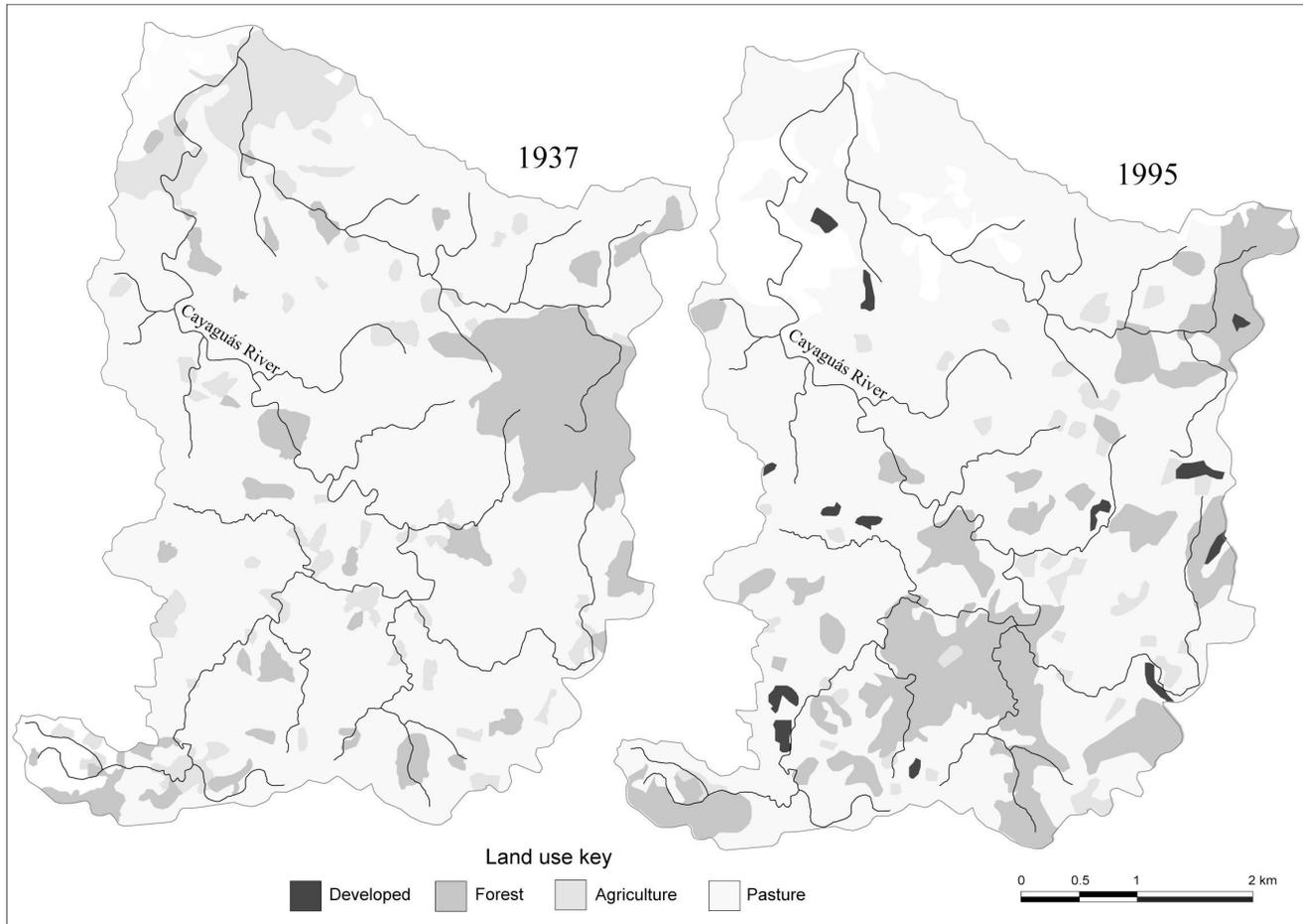


Figure 4 Generalized land use for 1937 and 1995 classified from black and white aerial photography, Cayaguás watershed, Puerto Rico.

Landslides

Most landslide scars mapped from aerial photographs predate the earliest available photographs (1937) and oral histories of local residents. Seventy percent of landslides mapped from 1951 and 1995 aerial photographs were present on the 1937 photographs. It is likely that accelerated rates of landsliding began in the early 19th century with the onset of forest clearing for agriculture. The causative storm events for landslide scars are therefore difficult to ascertain. The greatest rainfall intensities and widest distribution of storm rainfall in Puerto Rico usually are associated with tropical disturbances, which comprised 61% of the landslide-triggering storms recorded in the central mountains of Puerto Rico between 1960 and 1990 [Larsen and Simon, 1993]. Major hurricanes crossed the island in 1867, 1899, 1928, 1932, and 1960. These storms delivered precipitation totals of 300 to 800 mm in a 1 to 3 day period, and are the likely type of storm rainfall that triggered many of the landslide scars visible in the aerial photographs [Scatena and Larsen, 1991]. Conversations with watershed residents confirm that rainfall associated with hurricanes is commonly the trigger for landslides. This relation was observed following Hurricane Hortense (September 1996) and Hurricane Georges (September 1998) when dozens of debris flows, many extending from ridge top to the stream channel, were observed throughout the watershed (Fig. 5) [Torres-Sierra, 1997]. The rainfall totals from these two hurricanes had recurrence of intervals of 5 to 10 years in the Cayaguás watershed. The influx of landslide-derived and other sediment into channels resulted in 1.3 m of aggradation of the Cayaguás channel bed at the gage outlet following Hurricane Hortense [Larsen, 1997]. The channel bed surface was sustained at this elevation for three years before gradual degradation began in late 1999.

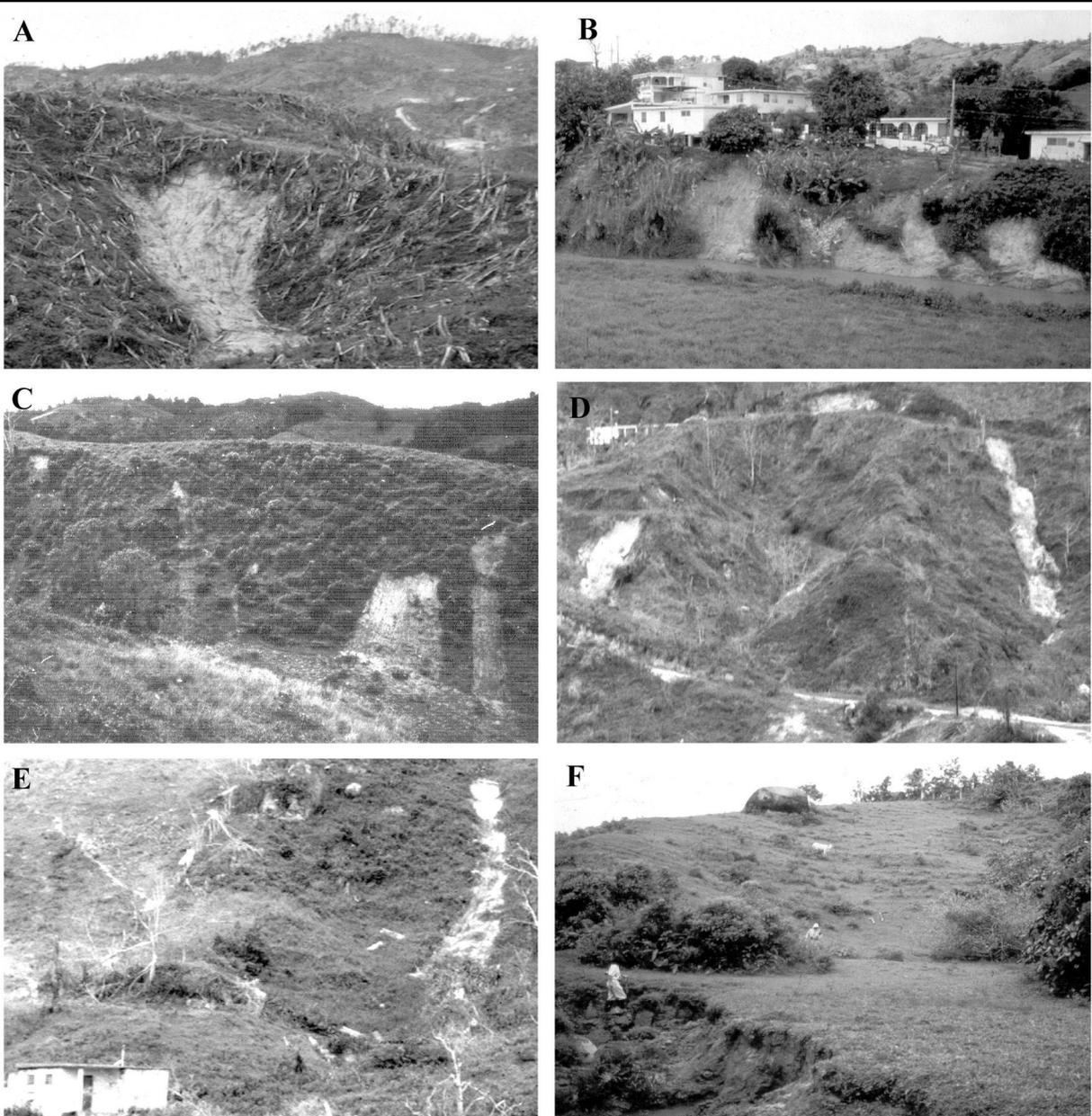


Figure 5. Views of landslide scars and stream channel headcutting associated with Hurricanes Hortense (September 1996) and Georges (September 1998) in the Cayaguás watershed, Puerto Rico. (A) Soil slip, 10 m long, on hillslope plantain field, September 1998. (B) Soils slips along Cayaguás tributary, September 1996. (C) Soil slips, 20 to 30 m long, September 1996. (D) Soil slip/debris flows, 10 and 30 m long, September 1998. Note larger deep landslide scar between the two recent ones. (E) Soil slip/debris flow, September 1998. (F) Headcut of first-order stream in colluvium at base of hillslope. Note large granodiorite corestone on ridgetop.

A total of 2,321 landslides were mapped from aerial photographs in selected portions of the watershed (Table 3). Landslide scars generally were small with a median length of 42 m, and affected a median surface area of 610 m², reflective, as noted above, of the high-intensity and short-duration nature of triggering rainstorms. The mean and median hillslope angles at landslide scars were both 25° (standard deviation: 6°, range: 10 to 38°, n: 159). Most landslides (77%) were on hillslopes with angles between 20 and 30°.

Landslide scar dimensions estimated from aerial photographs compared reasonably well to measurements made on the ground for length, but not as well for width and depth (Fig. 6). This result was expected as landslide scar length is relatively easy to determine while width and depth are more subjective, both from aerial photographs, as well as on the ground. The majority of scars have been modified by processes such as slopewash, trampling by cattle, plowing, and additional slumping on the side and head scarps [Trimble and Mendel, 1995; Larsen *et al.*, 1999]. This results in rounded head and side scarps and irregular scar depths that prevent precise measurements on the ground, as well as from the air (Fig. 7). The area, volume, and eroded mass of landslide scars discussed below are, therefore, approximations. The length, width, and depth of landslide scars measured on aerial photographs were adjusted using the equations shown in Figure 6.

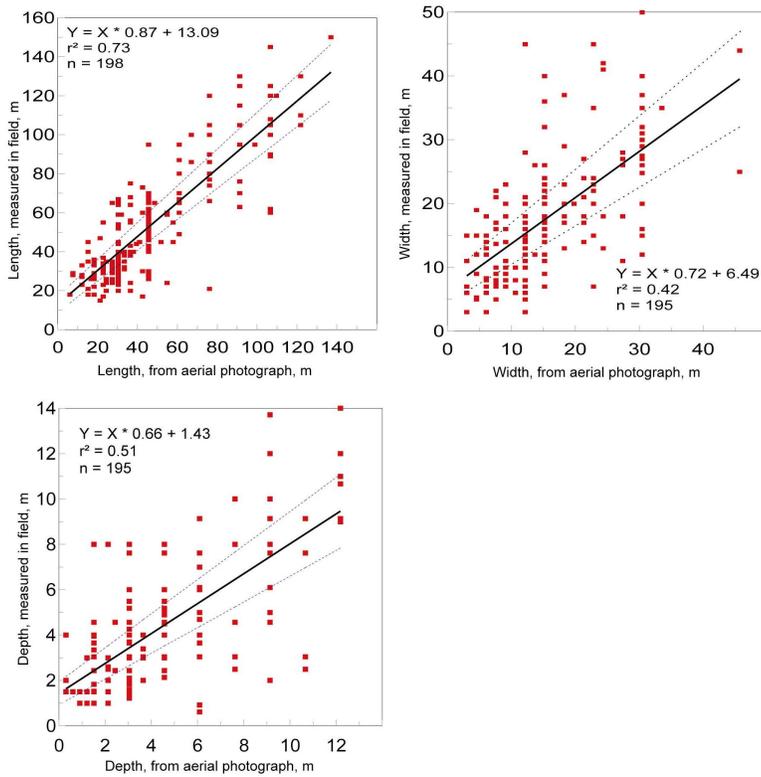


Figure 6. Relation between length, width, and depth of landslide scars measured in the field and measurements estimated from 1:20,000-scale aerial photographs, Cayaguás watershed. Simple linear regression models predict actual landslide scar dimension from that estimated using aerial photographs. Dashed lines show 95 percent confidence interval.



Figure 7. Amphitheater-shaped landslide scars and cow terracettes (created by cattle moving on preferred paths parallel to the slope contour), Cayaguás watershed. Landslide scar morphology is subdued because of past agricultural activity and grazing. Much of the soil and saprolite eroded by the mass wasting in this watershed remains in storage in deposits 3 meters thick on footslopes and small (zero-order) valley bottoms such as that shown here.

Most landslide scars, 61%, were classified as debris flows (Table 2). Soil slips, 23%, were the second most common type of scar. Both of these landslide types are characteristic of high-intensity, short-duration storms in Puerto Rico in which 24-hour rainfall totals are on the order of 200 mm [Larsen and Simon, 1993]. Storms of this magnitude have about a 5-year recurrence interval [U.S. Department of Commerce, 1961]. The remaining landslide scars were classified mainly as slumps, debris avalanches, and complex. About 1% of the landslide scars could not be categorized because of poorly defined features.

Table 2. Classification of 2,321 landslides by type in the Cayaguás watershed. Note, some totals may appear incorrect due to rounding.

Landslide type	Number	Percent
Debris flow	1,421	61.2
Soil slip	542	23.4
Slump	147	6.3
Debris avalanche	104	4.5
Complex	84	3.6
Undetermined	22	0.9
Earthflow	1	0.0

Table 3. Summary of dimensions of 2,321 landslides mapped from aerial photographs (1937, 1951, and 1995) covering a 16.6 km² area of the Cayaguás watershed, Puerto Rico. The length, width and depth of landslide scars measured on aerial photographs and reported below were adjusted using linear regression models developed from comparison of ground-based and photograph measurements (Fig. 6). Range for total area, volume, and mass reflects the minimum and maximum estimates for length, width, and depth.

	Median	Mean	Standard error	Total
Length, m	42	53	0.66	
Width, m	14	16	0.18	
Depth, m	3.4	3.5	0.04	
Surface area, m ²	610	980	24.43	
Volume, m ³	1,800	4,700	213.63	
Mass, Mg	6,200	2,300		
Total surface area, million m ² (range: 1.49 to 3.22)				2.27
Total volume, million m ³ (range: 5.57 to 18.8)				10.9
Total mass, million Mg (range: 7.35 to 24.9)				14.4
Landslide scars/km ²		140		
Landslide surface area, m ² /km ²		140,000		
Percent of basin surface area		14		
Landslide volume, m ³ /km ²		660,000		
Total surface lowering averaged over study area, m		0.66		
Landslide mass, Mg/km ²		870,000		
Landslide mass, Mg/km ² /y (1820 to 1995)		5,000		
Landslides/km ² /100 y (1820 to 1995)		80		

Landslide frequency was 140 scars/km², which, for an estimated period of about 175 years, equals 80 landslides per km²/100 y (Fig. 8). Mean soil density was determined to be 1.32 Mg/m³. This value exceeds that measured in nearby undisturbed forest where the effects of compaction from grazing and agriculture are absent and also reflects the abundance of dense clay [Larsen, 1997; Larsen et al., 1999; Simon et al., 1990]. The combined total surface area of all landslide scars was 2.27 million m² and the total mass equaled 14.4 million Mg (Table 3). Normalized to the watershed area, these values equal 140,000 m²/km² and 870,000 Mg/km², respectively.

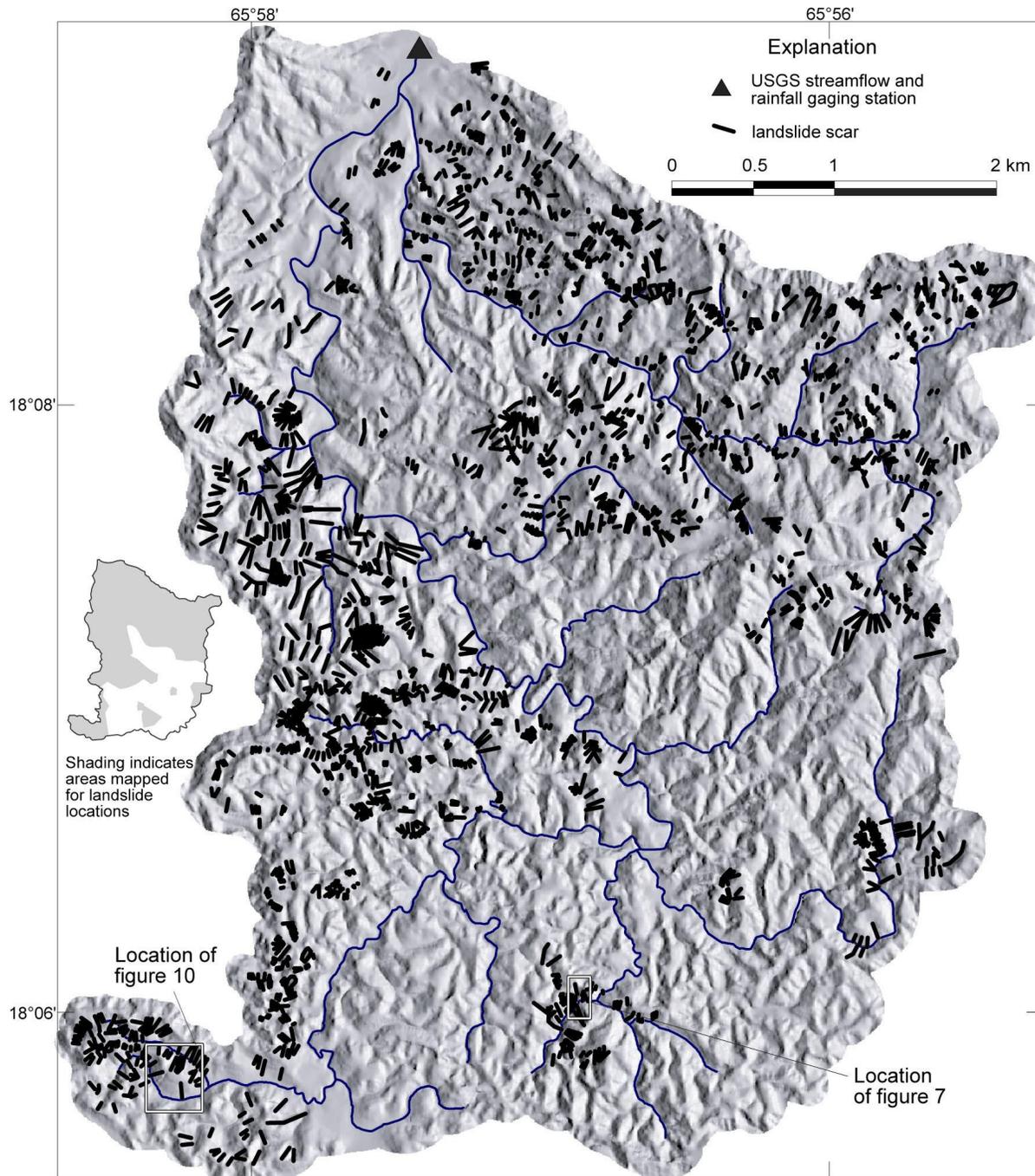


Figure 8. Shaded relief map of the Cayaguás watershed showing the location of 2,321 landslide scars mapped in a 16.6 square kilometer area (inset map shows area in which landslide scars were mapped) from 1937, 1951, and 1995 aerial photographs.

The volume of landslide scars totaled 660,000 m³/km². If all colluvium was transported from the catchment, then the volume would be equivalent to a mean surface lowering of the entire watershed by 660 mm, or 3.8 mm/ y (Table 3). This is an extremely high rate of erosion, on the order of the accelerated rate of 8.5 mm/y documented at open-pit mines and construction sites in the United States [Saunders and Young, 1983; Summerfield, 1991]. The erosion rate of 3.8 mm/y is comparable to the anthropogenically induced erosion of 5 mm/y of soil and saprolite estimated for the Cayaguás watershed using the cosmogenic isotope of beryllium, ¹⁰Be, documented by Brown et al. [1998]. Despite the high erosion rate, a large portion of the colluvium remains in the watershed.

Fluvial Sediment

The accurate determination of watershed sediment transport rates may require decades of sampling because of the importance of a few extreme events, as well as uncertainties due to changing land-use effects [Dietrich and Dunne, 1978; Meade, 1982; Nordin, 1985]. The data discussed below are, therefore, preliminary because of the short time period sampled.

Mean annual fluvial sediment yield, which includes suspended and bedload sediment for the 8 years with available data, was 2,570 Mg/km²/y. Fluvial sediment yield was extremely low, 252 Mg/km², in 1991 when runoff was only 47% of the mean compared to a high of 8,570 Mg/km² in 1985, when runoff was 138% of the mean of 1,480 mm (Table 4). The largest storm of 1991 had a mean daily discharge of only 6.2 m³/s. In comparison, there were 17 storms in 1985 with mean daily discharge that exceeded 6.2 m³/s; the largest storm recorded in 1985 had a mean daily discharge of 53.5 m³/s. This great interannual variability in discharges strongly influenced the mobilization and transport of fluvial sediment. The large difference (factor of 34) between sediment yield in 1985 and 1991 emphasizes the well known problem of characterizing mean annual fluvial sediment yield with few years of data. The mean annual sediment yield for the 5 years of data representing the 1990's was only one-fourth that of the mean annual sediment yield for the 3 years of data collected in the 1980's. As is typical of many small watersheds, most of the annual sediment load was transported out of the watershed in a few days. For example, in 1985, the year with the greatest sediment yield, 63% of the annual yield occurred during a 5-day storm.

Table 4. Annual fluvial sediment discharge and runoff from the Cayaguás watershed, Puerto Rico [Guzmán-Ríos, 1989; Larsen, 1997; Simon and Guzmán-Ríos, 1990; U.S. Geological Survey, 1999). Mean annual runoff, 1977_95, is 1,480 mm.

Year	1984	1985	1986	1991	1992	1993	1994	1995	Mean, 1980's	Mean, 1990's	Mean, all years
Suspended sediment yield, Mg/km ²	1,360	4,970	2,230	97	2,030	1,090	341	177	2,850	746	1,540
Bed_material yield, Mg/km ²	984	3,600	1,620	154	497	785	382	268	2,070	417	1,040
Total fluvial sediment, Mg/km ²	2,340	8,570	3,850	252	2,530	1,870	723	445	4,920	1,160	2,570
Runoff, mm/y	1,330	1,990	1,730	678	1,360	1,660	940	920	1,690	1,110	1,330
Annual runoff/mean	0.90	1.34	1.17	0.46	0.92	1.12	0.63	0.62	1.17	0.77	0.92

Sediment Storage

Channel widths were measured at 38 locations in the watershed and showed a pattern typical of fluvial systems where the increase in width with stream order defines a linear trend in semi-log space (Fig. 9; Tables 5,6). A total of 1.6 km of stream channel was surveyed to measure the dimensions of channel bars (Table 5). This length of channel represents a channel surface area of 14,500 m². Mean channel bar thickness was 0.12 m and, using a mean density of 1.14 Mg/m³ measured for sand bar deposits, the mean bar mass was 21 kg/m² of channel. A total of 5,300 Mg of sediment was calculated to be in active storage in channel bars (Table 6). Sediment in the other active compartment, the channel bed, was calculated to be 216,000 Mg. Using a 1.5-m mean thickness of alluvium and 3 m of colluvium thickness, the quantity of sediment stored in floodplains was estimated to be 1.79 million Mg; colluvial storage was about double this at 3.94 million Mg (Table 7). These two compartments are defined as semiactive. Inactive sediment, defined as that stored in approximately 4-m thick deposits of Quaternary alluvium, was calculated to be 0.68 million Mg. These data indicate that only a small portion of watershed sediment, 3.3%, exists in active storage compartments (Table 8). The majority of sediment, 87%, is in the semiactive compartments (i.e., floodplains and colluvium). The remainder, about 10%, is in Quaternary alluvium.

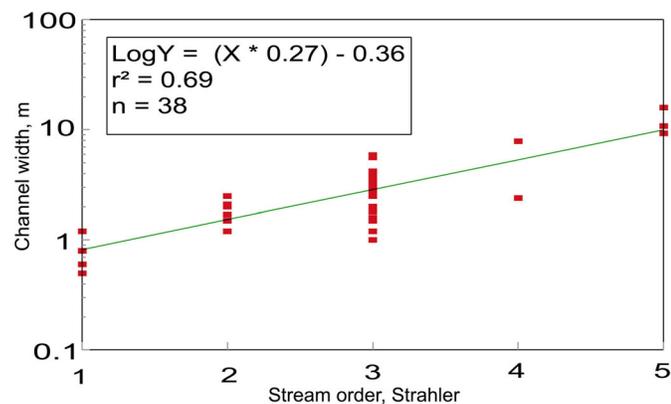


Figure 9. Relation between channel width and Strahler stream order in the Cayaguás watershed.

Table 5. Summary of field survey of channel bar dimensions and distribution in the Cayaguás watershed. Density of sediment is 1.14 Mg/m³.

Channel bar thickness, mean, m (n=134)	0.12
Surveyed channel bar surface area, total, m ²	2,500
Surveyed channel length, total, m	1,580
Channel bar area, mean, m ² /m of channel length	1.44
Channel area surveyed, m ²	14,500
Bar sediment, mean, kg/m ² of channel	21

Table 6. Stream channel dimensions and estimates of sediment in active storage compartments in the Cayaguás watershed. Channel lengths determined using GIS software analysis of digital elevation model. Channel widths derived from field-based model (see fig. 7). Estimates of the quantity of sediment in channel bars and bed derived from field surveys. Note, some totals may appear incorrect due to rounding.

Stream order	Length, m	Mean width, m	Area, m ²	Estimated mean bed thickness, m	Total bed sediment, Mg	Total bar sediment, Mg
1	83,900	0.82	68,800	0.02	1,600	450
2	44,500	1.53	68,100	0.05	3,900	890
3	23,500	2.85	67,000	0.5	38,200	1,750
4	9,600	5.32	50,900	1	58,000	1,560
5	10,100	9.93	101,000	1	115,000	630
Total	172,000		355,000		216,000	5,300

Table 7. Estimated sediment in semiactive (floodplain) and inactive (Quaternary alluvium) compartments, Cayaguas watershed. Mean floodplain thickness is 1.5 m, Quaternary alluvium thickness estimated at 4 m, and mean colluvium thickness is 3 m. Mass was calculated using a density of 1.14 Mg/m³.

	Area, m ²	Volume, m ³	Mass, Mg	Mass, Mg/km ²
Floodplains (semiactive)	1,040,000	1,570,000	1,790,000	67,600
Quaternary alluvium (inactive)	150,000	598,000	682,000	25,800
Colluvium (semiactive)	1,150,000	3,460,000	3,940,000	149,000

Table 8. Summary of sediment stored in active, semiactive, and inactive compartments in the Cayaguas watershed, Puerto Rico. Note, some totals may appear incorrect due to rounding.

	Mass, Mg	Mass, Mg/km ²	Percent
Channel bars (active)	5,300	200	0.1
Channel bed (active)	216,000	8,200	3.3
Floodplains (semiactive)	1,790,000	67,600	26.9
Colluvium (semiactive)	3,940,000	149,000	59.5
Quaternary alluvium (inactive)	682,000	25,800	10.3
Total	6,630,000	251,000	

DISCUSSION

Landscape conversion in the Cayaguás watershed was carried to an extreme by 19th- and early 20th-century subsistence farmers who had removed at least 88% of the forest cover by 1937 (Fig. 3). It is probable that the farmers had eliminated even more forest cover prior to 1937, but aerial photographic documentation is not available. The removal of forest cover and subsequent intense year-round agriculture seems to have greatly accelerated hillslope erosion, as noted in other areas where human landscape disturbance is followed by very high erosion rates, at least immediately after the disturbance [Montgomery *et al.*, 2000]. The nearby Iacos watershed, which is located in the Luquillo Experimental Forest and consists of primary forest with comparable bedrock geology (quartz diorite)

and a mean slope (22% or 12.4°) has lower rates of landsliding (43 landslides/km²/y), fluvial sediment yield (954 Mg/km²/y), and sediment storage on footslopes [Larsen, 1997; Larsen and Torres-Sánchez, 1998; Larsen et al., 1999]. This, in spite of more than double annual rainfall, 4,156 mm, in the Icos watershed.

The number of landslide scars in the Cayaguás watershed, at 140 landslide scars per km², is the highest ever documented for Puerto Rico. Few studies elsewhere in the world have described landscapes of comparable area with greater densities of landslide scars. Scenes such as those shown in Figures 5, 7, and 10, are typical of the watershed: hillslopes are striated with numerous debris flow and soil slip scars and valley floors and footslopes are mantled with several meters of colluvium. No colluvium samples were dated but anecdotal evidence that colluvial material dates from the period of European forest clearing is suggested by the sharply angular form of wood and charcoal fragments present at several locations. The fragments appear to have been cut by a sharp-bladed instrument such as a machete, commonly used by farmers from the 19th century to the present.

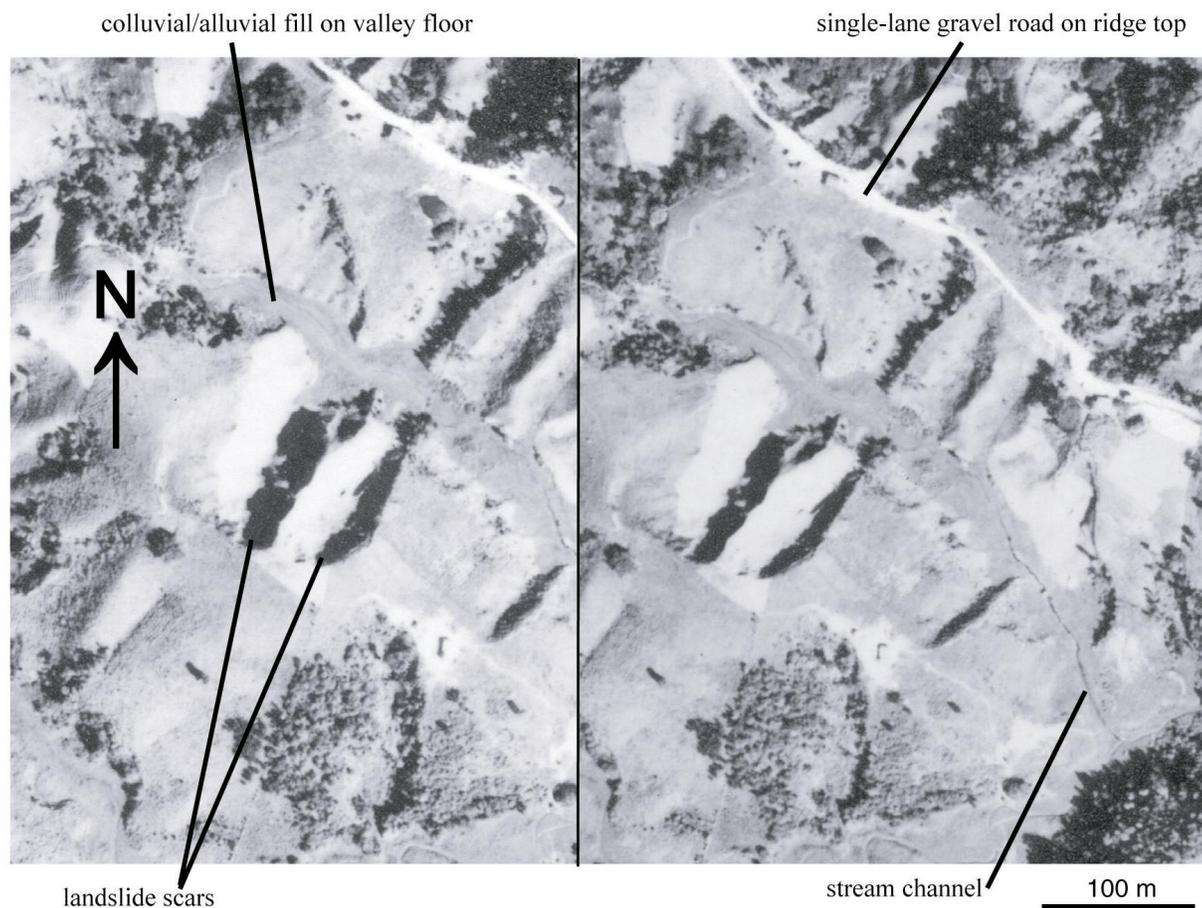


Figure 10. Stereo aerial photographs of southeastern Cayaguás watershed, Puerto Rico, 1951, showing 15 landslide scars of various ages, and sediment stored as colluvial/alluvial fill on valley floor. Sunlight from right (east) side of photographs. Second-order stream flows towards southeast.

Figure 10, which can be viewed in three dimensions with a stereoscope, highlights the abundance of landslide scars and their effect on hillslope morphology and land use. Landslide features dominate most of the hillslopes in the pair of photographs. Farmers have adapted to these conditions by planting plantains or grazing cattle on hillslopes, in spite of the presence of landslide scars. Landsliding, slopewash, and soil creep have shifted much of the nutrient-rich topsoil from the hillslope to the valley bottom. This large-scale, relatively rapid movement of sediment to valley floors which began in the 19th century, seems to have inhibited the pre-disturbance relatively rapid channel development here and elsewhere in the watershed, and has created a boggy, poorly drained substrate. On the colluvium- and alluvium-filled valley floors that result from these processes, farmers raise *Colocasia esculenta*, (malanga) the crop, noted above, that tolerates saturated soil conditions (Fig. 10). The most profound aspect of the rate of mass wasting in this watershed is the total volume of material shifted from hillslopes and moved to footslopes and river channels. This volume, 10.9 million m³, indicates that, on average, the ground surface in this watershed was lowered by 660 mm in approximately 175 years, attesting to the remarkable effectiveness of humans as geomorphic agents (Table 3) [Osterkamp, 2000].

A conceptual geomorphic model of landform development for the Greater Antilles proposed by Ahmad et al. [1993] postulates that landsliding is the major contributor of sediment to stream channels. This concept has also been proposed for the Lesser Antillean island of Dominica by Reading [1986], who stated that landslides are the most important mechanism by which sediment is supplied to rivers. These models are supported by the present work in the Cayaguás watershed. Erosion of hillslopes is dominated by episodic mass-

wasting processes, mainly landsliding, which, at decadal or greater time scales, deliver orders of magnitude more sediment to stream channels than all other hillslope-erosion processes combined [Larsen, 1997, Larsen et al., 1999, Gellis et al., 1999].

GIS analysis indicates that 1.15 million m³ of the Cayaguás watershed has hillslopes of 10° or less, if ridgetops, floodplains, and river channels are excluded. If 3 m of colluvium are evenly distributed on these low-slope surfaces, a volume of 3.46 million m³ is present in the watershed (Table 7). By subtracting this volume from the total volume of historic landslide scars in the Cayaguás watershed (10.9 million m³), the difference, 7.44 million m³ (282,000 m³/km²), provides an estimate of the amount of fluvial sediment export that may have occurred since deforestation began in 1820. Converting the difference to mass, 0.32 million Mg/km² of sediment may have passed the watershed outlet, equivalent to an average annual yield of about 1,800 Mg/km². This estimate may be low, but is reasonable, as the sediment yield during the years sampled in the 1980's and 1990's averaged from 1,160 Mg/km²/y (1990's) to 4,900 Mg/km²/y (1980's) (Table 4). It is assumed that during peak agricultural use of the watershed sediment yield was higher than the 1990's rate. Other evidence suggesting that 1,800 Mg/km² is reasonable, but may be a conservative approximation for the period of peak agricultural activity in the Cayaguás watershed, is obtained from a comparable site in the Greater Antilles. Estimated annual soil erosion in the humid central mountains of the Dominican Republic, where shifting cultivation and monoculture is still practiced, ranges from 5,930 to 6,930 Mg/km²/y [Altieri, 1990].

The mean landslide rate, 0.8/km²/y, is equal to 5,000 Mg km²/y (median landslide mass of 6,200 Mg times 0.8), which could explain more than 100% of the annual fluvial sediment yield (Tables 3, 4). Another source of fluvial sediment observed, but not quantified in this study, is the erosion of channel banks and flood plains caused by high flows. The 0.8/km²/y landslide rate exceeds the contribution to sediment yield from landslides during recent years, especially when considered with other sources of fluvial sediment. Nonetheless, new landslides occurred during the period of study and many old scars are observed to be actively eroding in the Cayaguás watershed. Furthermore, hillslope lengths are short and many scars extend from ridgetop to stream channel, so landslide-derived sediment can be delivered directly to the fluvial system (Fig. 5B,10). Slopewash of 10 to 86 Mg/km²/y account for only a small portion of overall fluvial sediment yield. Although the contribution was not determined in this study, gullying provides a minor portion of fluvial sediment yield. The abundance of landslide scars and the degree of channel aggradation following Hurricane Hortense are dramatic evidence of the substantial role of episodic landslide-induced erosion in this watershed.

The storage of colluvium is extensive in the Cayaguás watershed. Storage of sediment is noted even in the headwaters of the Cayaguás watershed where contributing areas apparently limit runoff to below the competence required to erode valley-bottom deposits, except during infrequent events (Figs. 7,10). Another factor limiting the transport of colluvial sediment and channel development in some headwater areas is the effect of cattle on the bottomland soil surface. The combination of high annual rainfall and random grazing patterns on these relatively low gradient surfaces has resulted in saturated, poorly drained soil with very limited channel development. Standing water with depths of several 10's of cm occurs in pools created by cattle hoof prints and is widespread during most of the year at the heads of drainages. Nonetheless, field observations at dozens of sites immediately down-gradient of such areas indicate that recent headcutting into colluvium is active in the Cayaguás watershed (Fig. 5F). This suggests that at least some of the fluvial sediment now being transported out of the watershed is derived from sediment stored in semiactive compartments (floodplains and colluvium) deposited perhaps as long ago as the 1800's. The estimated amount of colluvium remaining in the watershed, 3.94 million Mg, is a 30- to 129-year supply of sediment at the 1980's and 1990's transport rates, respectively (Table 7). Although these calculations are based on a series of approximations, they provide a means to evaluate historic transport rates, estimate colluvial storage, and predict the potential mass of material available for fluvial transport out of the watershed.

The determination of the mass of sediment available for transport in the Cayaguás watershed (and other Río Grande de Loíza upland watersheds within the boundaries of the San Lorenzo batholith) is of more than theoretical interest. The Loíza Reservoir is downstream of the Cayaguás River (Fig. 1). This 267-ha reservoir is the source of about 50% of the water supplied to the 1.6 million inhabitants of metropolitan San Juan, at an average daily rate of 302,000 m³ [Webb and Soler-Lopéz, 1997]. Sediment has accumulated in the reservoir at annual rates ranging from 110,000 m³ to 452,000 m³ since the first bathymetric survey in 1963. These volumes are equivalent to an annual capacity loss of 1.1 to 1.5%, and indicate that average sediment yield from the basin has fluctuated between 750 and 900 Mg/km², assuming an average trap efficiency of 75% [Webb and Soler-Lopéz, 1997]. Current infilling is estimated to be 242,000 Mg/y. The current 1,160- to 4,920-Mg/km²/y annual sediment yield from the Cayaguás watershed, (which represents only 5% of the 538 km² contributing area of the reservoir) is 31,000 to 130,000 Mg, or an impressive 13 to 54% of the total annual reservoir sediment input. In addition, the estimated volume of colluvial storage in the Cayaguás watershed was approximated above to be 3.5 million m³. The current capacity of the Loíza reservoir has been computed to be 14.2 million m³. A high-magnitude storm, if able to mobilize a large portion of this stored sediment, could have a severe impact on reservoir storage and the San Juan water supply. Mitigation is expensive: in 1998-1999, 5 million m³ of sediment was dredged from the reservoir at the cost of \$12/m³ [Vega and Terrasa-Soler, 1998].

The Cayaguás mass-wasting erosion and fluvial-sediment transport rates described above are high for the island of Puerto Rico. Even on geologic time scales, landscape denudation in the Cayaguás watershed seems to have been extreme. This is observed on topographic maps where the region underlain by the intrusive bedrock in southeastern Puerto Rico is anomalously lower than surrounding non-intrusive bedrock terrain. The San Lorenzo batholith appears as an extensive area of highly weathered rock with reduced relief compared to the ridges bounding the batholith along the western and southern margins (Fig. 1).

CONCLUSIONS

Landslide frequency in the Cayaguás watershed is the highest documented for the island of Puerto Rico, and is high compared to rates published for watersheds of comparable size elsewhere [Summerfield, 1991]. Mass wasting enhanced by human activity during the last two centuries has, on average, lowered the land surface of the watershed at the rate of 3.8 mm/y. Based on landslide frequency, the storage of colluvium, and annual fluvial sediment yields, hillslope processes that were triggered as long ago as 1820 by the onset of forest clearing, maintained high sediment yield during the 20th century and will probably affect fluvial sediment yield for most of the 21st century. This is sobering news to governments attempting to manage landscapes and watersheds in a sustained manner.

Land-use conversion in the Mediterranean-European region required several millennia and occurred in North America during a few centuries. In the humid tropics, it is occurring at a far more rapid rate, measureable in decades. In the context of inexorable population growth and increasing resource consumption, the impacts of development on natural systems in the low-latitude regions have, therefore, never been more intense than at the present time. The adverse effects of forest cutting, agricultural expansion, and urbanization are recognized at the global scale and are international concerns [Osterkamp, 2000].

What does the future hold? A rational appreciation of development processes in the humid tropics necessitates educated debate and compromise on how landscapes are to be converted or managed in the near and long term. Sustainable development of natural resources requires accumulation of extensive knowledge of geomorphic processes and sediment budgets in undeveloped and developing regions. The data base in the tropics is limited. One objective of this study was to contribute to that knowledge. Puerto Rico is uniquely positioned to provide a glimpse into the future for humid-tropical environments in that removal of forest and conversion of landscapes to agriculture peaked about 50 years ago. Subsequent industrial growth has allowed forests to recover as the agricultural sector has contracted. This setting is comparable to what might be expected during the 21st century in the impacted areas of Africa, Asia, and Amazonia, and therefore merits close scrutiny.

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