Effects of land-use change on channel morphology in northeastern Puerto Rico

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ABSTRACT

Between 1830 and 1950 much of northeastern Puerto Rico was cleared for agriculture. Runoff increased by ~50% and sediment supply to the river channels increased by more than an order of magnitude. Much of the land clearance extended to steep valley slopes, resulting in widespread gullying and landslides and a large load of coarse sediments delivered to the stream channels. A shift from agriculture to industrial and residential land uses over the past 50 yr has maintained the elevated runoff while sediment supply has decreased, allowing the rivers to begin removing coarse sediment stored within their channels. The size, abundance, and stratigraphic elevation of in-channel gravel bar deposits increases, channel depth decreases, and the frequency of overbank flooding increases downstream along these channels. This is presumed to be a transient state and continued transport will lead to degradation of the bed in downstream sections as the channel adjusts to the modern supply of water and sediment. A downstream decrease in channel size is contrary to the expected geometry of self-adjusted channels, but is consistent with the presence of partially evacuated sediment remaining from the earlier agricultural period. Reverse (downstream decreasing) channel morphology is not often cited in the literature, although consistent observations are available from areas with similar land-use history. Identification of reverse channel morphology along individual watercourses may be obscured in multiwatershed compilations in which other factors produce a consistent, but scattered downstream trend. Identification of reverse channel morphology along individual streams in areas with similar land-use history would be useful for identifying channel disequilibrium and anticipating future channel adjustments.

Keywords: channel response, geomorphology, land use, Puerto Rico, sediment supply.

INTRODUCTION

Land-use changes alter the water and sediment supplied to rivers, which, in response, alter their geometry and composition toward a condition capable of passing the supplied sediment with the available water. Changes in water and sediment input can result from a wide variety of land uses, including mining operations (Gilbert, 1917; Pickup and Warner, 1984; Higgins et al., 1987; Knighton, 1989; James, 1991), timber harvesting (Varnum and Ozaki, 1986; Madej and Ozaki, 1996), agriculture (Happ et al., 1940; Costa, 1975; Knox, 1972, 1977, 1987; Trimble, 1974, 1981, 1983; Trimble and Lund, 1982; Jacobson and Coleman, 1986; Jacobson and Pugh, 1992; Jacobson, 1995; Knox and Hudson, 1995; Ruhlman and Nutter, 1999), urbanization (Wolman, 1967; Wolman and Schick, 1967; Hammer, 1972; Fox, 1974; Park, 1977; Ebisemiju, 1989), or mixtures of different land uses (Miller et al., 1993)

Although the general cause and effect relation between water and sediment supply and channel change is clear, the range of possible channel response is diverse. The rate and direction of changes in channel width, depth, or composition can vary with the relative magnitude of changes in water and sediment supply, as well as the caliber of sediment supply (Lane, 1955; Schumm, 1969). Adding to the complexity is the fact that land-use changes are usually distributed in time and space. Channel response may lag behind land-use change and will often integrate the effects of a complex sequence of spatially and temporally variable land-use patterns. The result is that the channel response to any particular land use is difficult to isolate and most modern channels in developed regions exhibit an incomplete and spatially varying response to the suite of previous land-use changes.

An additional complication is that there is often little known of a river's previous geometry, composition, or water and sediment loads. Despite the complex nature of the problem and the incomplete information available to address it, there are important reasons for unraveling a river's history; the most important of which is to provide a basis for estimating future channel changes. Many attempts to modify or restore rivers take little account of the river's history and the underlying factors producing the channel conditions motivating the need for action. The natural complexity of river channels, the spatial and temporal variation in the controlling factors, and the long time scale of channel response make direct prediction from present conditions speculative. In the absence of reliable historical information, it is necessary to read the channel history from its present geometry and from any stratigraphic information that may be available.

In this paper we examine river channel response to pervasive land-use changes in three watersheds in northeastern Puerto Rico. There is little historical evidence of previous watershed or channel conditions, so we turn to stratigraphic evidence and examine trends in the present channel geometry for indications of channel response to changes in land use. Of

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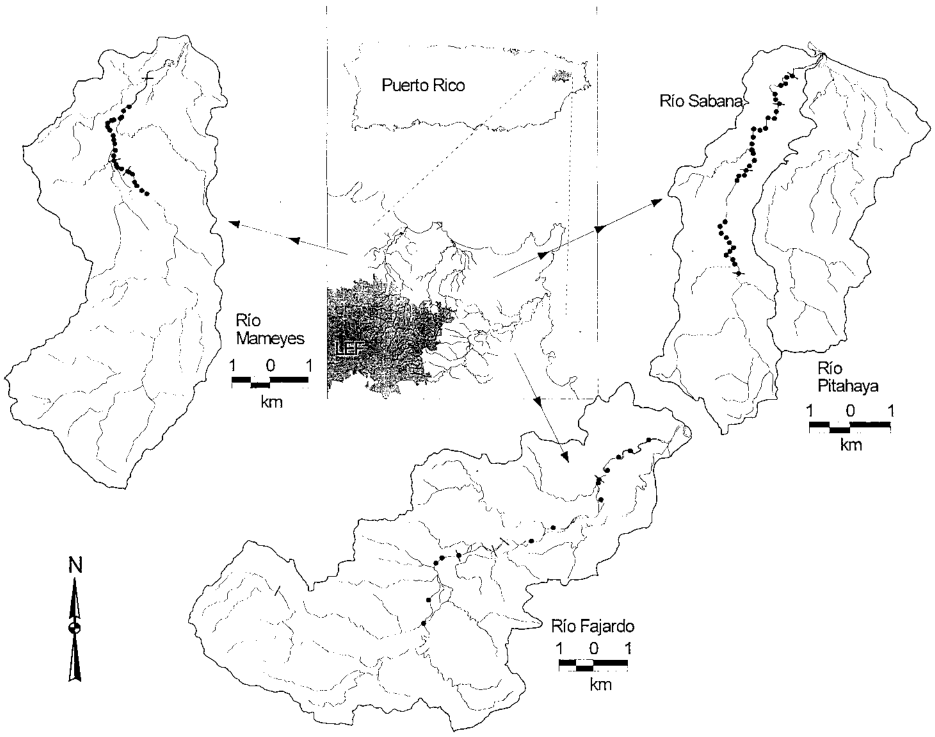

Figure 1. Location map of northeastern Puerto Rico and the three rivers studied. These watersheds all drain the Luquillo Experimental Forest (LEF). Cross-valley core sections are denoted by tick marks and channel cross sections are denoted by filled circles. Note different scales used on the inset maps.

particular importance are downstream variations in channel geometry, flow frequency, and fluvial stratigraphy, which we compare to observations and assumptions made in other regions. Such alternative means for demonstrating channel change are motivated not only by the typical absence of reliable historical information, but also by the need to forecast future channel adjustments in areas of similar land-use change.

The land-use history in northeastern Puerto Rico (a sustained period of widespread and intensive agriculture, replaced by residential and/or urban uses or secondary growth forest) is common to many areas of European colonial development. The effect of this land-use pattern on rivers has been described for North America (e.g., Knox, 1972, 1977, 1987; Trimble, 1974; Trimble and Lund, 1982; Jacobson and Coleman, 1986; Miller et al., 1993; Ruhlman and Nutter, 1999) and Australia (Gregory, 1977; Nanson and Young, 1981). Less work has been done in tropical regions (Gupta, 1975, 1982; Ebisemiju, 1989), although trends in population growth and urbanization in the tropics suggest that this land-use sequence will become increasingly common.

STUDY AREA

Northeastern Puerto Rico (Fig. 1) has a humid subtropical climate influenced by easterly trade winds, local orographic effects, and hurricanes (Monroe, 1980). Annual rainfall varies from 4.5 m in the mountainous headwaters to 1.5 m along the coastal plain. Rainfall is weakly seasonal; tropical disturbances and hurricanes occur between September and November, although slow-moving winter cold fronts can also deliver appreciable amounts of rain.

The source area for streams in northeastern Puerto Rico is the Luquillo Mountains, which rise to more than 1000 m in elevation and grade rapidly into the alluvial lowlands, dropping 950 m in elevation in just 5 km. Alluvial valleys are bounded by steep bedrock hills rising to more than 150 m in elevation. Bedrock is composed primarily of Cretaceous marine sandstone, mudstone, and breccia of andesitic-basaltic composition, interbedded with andesitic lava (Sieders, 1971; Briggs and Anguilar-Cortez, 1980). These volcaniclastic rocks weather to clay that forms a thick (>5 m) saprolitic cover. Tertiary intrusions of quartz diorite and mafic dikes of diabase are the surficial bedrock in ~3% of the drainage basins and their weathering products are responsible for most of the sand found in the rivers.

Parts of three rivers are examined here: Rio Mameyes, Rio Sabana, and Rio Fajardo (Fig. 1). The watersheds of these streams drain most of northeastern Puerto Rico and have similar climate, physiography, drainage area, bedrock geology, and land-use history. Bed material decreases in size from boulders and cobbles ($D_{84} \approx 300$ mm) in upstream reaches to cobbles and gravel ($D_{84} \approx 100$ mm) in downstream reaches. The bed material becomes predominantly sand ~1 km from the ocean. This work focuses on the alluvial portions of these rivers, which are characterized by wide alluvial plains flanked by steep valley hillsides.

The Rio Mameyes drains a 44.5 km² north-south–trending watershed with steep bedrock valleys. The lower 5.5 km is alluvial; valley-bottom width increases to a maximum of nearly 900 m 1.5 km from the Atlantic Ocean. The Rio Sabana drains a narrow 35 km² north-south–trending watershed. The upper 5 km runs through steep v-notch bedrock valleys, grading into a short, narrow alluvial valley (50 m valley-bottom width) before passing over a nearly vertical bedrock waterfall. The remaining 6.5 km of the river is alluvial and valley-bottom width generally increases toward the ocean, reaching 460 m at its widest point 1.2 km upstream from the ocean. The Rio Fajardo drains a relatively wide 68 km² east-west–trending watershed and empties into Vieques Sound. The downstream 15.3 km is alluvial and valley-bottom width expands to just more than 1.2 km at the downstream end of the study reach. Study reaches are entirely alluvial; extending from the end of steep bedrock valleys to the head of the coastal plain, where the tide influences channel flow.

Each of the streams has a continuous recording gage with at least 18 yr of record. Mean annual discharge for these gages is 19.3 $m^3/s \cdot km^{-2}$ for the Rio Mameyes (gaged drainage area 17.9 km²; period of record 1969–1973, 1983–1997), 13.1 $m^3/s \cdot km^{-2}$ for the Rio Sabana (10.3 km²; 1980–1997), and 6.8 $m^3/s \cdot km^{-2}$ for the Rio Fajardo (38.8 km²; 1962–1997). Maximum peak instantaneous discharges are 580 m^3/s (32.4 $m^3/s \cdot km^{-2}$) for the Rio Mameyes, 255 m^3/s (24.8 $m^3/s \cdot km^{-2}$) for the Rio Sabana, and 665 m^3/s (17.1 $m^3/s \cdot km^{-2}$) for the Rio Fajardo. These gages, together with a discontinued gage on the Rio Mameyes and 5 other gages near the study area, give 9 gages with at least 15 yr of record and a wide range in drainage area (Table 1).

These records were used to develop regional discharge curves that are used later in this paper.

Because the focus of this paper is the interaction between channel morphology and changes in land use, it is useful to consider other factors, such as climate change and catastrophic storms, that might influence channel change over a comparable time period. Paleoenvironmental reconstruction–based oxygen isotope measurements from ostracods, and lake-level indicators from Lake Miragoane, Haiti, suggest that the Caribbean underwent a gradual reduction in rainfall relative to evaporation over the past 900 yr (Hodell et al., 1991; Higuera-Gundy et al., 1999). Although most rainfall tends to occur during the summer rainy season, changes in the frequency and magnitude of channel forming storm events are unknown. Therefore, we cannot infer any channel change to have taken place based on the proxy record of past climatic change.

Historical accounts of tropical storms and hurricanes provide a better measure of the changes in channel-forming storm and runoff events. Hurricanes pass over the island on average every 10–20 yr and tropical waves and depressions occur with even greater frequency (Scatena, 1989; Scatena and Larsen, 1991). Some clustering in hurricane occurrence occurs, and increased frequency is observed for the decades following 1770, 1780, 1810, 1830, and 1930 (Reading, 1990). Large hurricanes in 1928 and 1932 are notable because land disturbance was extensive during this time period. The largest floods are not necessarily associated with hurricanes (López et al., 1979). For example, although Hurricane Hugo (1989) produced the largest recorded peak discharge on the Rio Mameyes and Rio Fajardo, a cold front in 1992 produced the largest peak discharge on the Rio Sabana. The 1992 storm generated a peak discharge in the Rio Fajardo of nearly the same magnitude as Hugo, but had little effect on the Rio Mameyes. The frequency of floods in the study area relative to the multidecade to century time scale under consideration and the different orientation and runoff generation in the three basins suggest that channel changes observed across the basins are not likely to have been caused by a single catastrophic storm in the past 200 yr.

TABLE 1. CHARACTERISTICS OF GAGE STATIONS IN AND AROUND THE STUDY AREA

River	U.S. Geological Survey station number	Gaged area (km^2)	Length of record (yr)	Maximum discharge (m^3/s)
Grande de Loiza	50055000	232.8	31	2023
Valenciano	50056400	42.5	19	1132
Gurabo	50057000	155.9	31	2111
Espiritu Santo	50063300	5.78	15	271
Espiritu Santo	50063800	22.3	24	543
Mameyes	50065500	17.9	20	580
Mameyes*	50065700	30.7	17	741
Sabana	50067000	10.3	18	255
Fajardo	50071000	38.8	36	665

*Gage discontinued in 1984.

LAND USE IN NORTHEASTERN PUERTO RICO

Puerto Rico was first visited by Europeans during the second voyage of Columbus in 1493. Charcoal, post holes, and anthropogenic debris are found in some pre-European archaeological sites, indicating that there was some disturbance on the island prior to the arrival of Europeans. However, only one archaeological site has been documented within the study area, suggesting that disturbance has been minimal (Pantel, 1994, 1995). Moreover, unlike slash and burn agriculture utilized by many Indians in the tropics, the agriculture practiced by the native Taíno Indians was quite advanced. Rich alluvial soil was piled into large mounds and tubers planted within. These mounds minimized erosion and extended the lifetime of the plots, thereby requiring less land than other contemporary techniques (Rouse, 1992). Although extensive pre-European agricultural disturbance has been documented elsewhere (e.g., North America, Denevan, 1992; Doolittle, 1992), it was not severe in the Caribbean region (Higuera-Gundy et al., 1999).

Within 40 yr of European discovery, Puerto Rico had 10 sugar mills and a placer gold mine on the southern flanks of the Luquillo Mountains, although the presence of hostile Indians limited growth and forced settlers to abandon the northeastern portion of the island as late as 1582 (Wadsworth, 1950; Scatena, 1989). As the continental neotropics opened to development, European activities in Puerto Rico declined. There was little European development in the northeastern section of the island throughout the 1600s and 1700s.

European settlement and land development increased after 1815 when the Spanish Crown removed trade restrictions and opened Puerto Rico to world markets and immigration (Scatena, 1989). By 1828, timber cutting and agriculture began in earnest, reducing forest cover to about 66% of the island and causing timber scarcities along the coast (Birdsey and Weaver, 1987). Timber was exported from Fajardo between 1830 and 1890, and during this period nearly all wood products came from coastal and alluvial plains (Wadsworth, 1950). As lumber demands increased and supplies decreased, settlers were forced to exploit more marginal lands. Upland forests were thinned for coffee cultivation and cut for timber, fuel, and agriculture, leaving only the steepest, most inaccessible slopes undisturbed (Garcia-Montíel and Scatena, 1994).

Redistribution of land from the government to private individuals was initiated in 1830 and, together with free trade, served to further accelerate agricultural development. Entrepreneurs purchased large tracts of fertile lowlands in order to raise sugar cane for export (Scatena, 1989). Alluvial valleys in the study area were under extensive cane cultivation from ca. 1875 to 1940. Displaced residents and new arrivals were forced to clear the steep hillsides for subsistence agriculture. During the agricultural peak, homes were typically sparse in the cane-planted lowlands; most people lived in nearby towns and on the valley hillsides (Pico, 1974).

By 1900, 80% of the island was under agriculture (Birdsey and Weaver, 1987) and lumber scarcities forced developers to import building supplies and harvest steeper upland areas (Pico, 1974). Gleason and Cook (1926) noted that settlement and agriculture in the lowlands were extensive enough to limit native forest vegetation to scattered wood lots and small strips along some streams and fence rows. Conservation practices such as crop rotation, mulching, and cover crops were virtually absent during the agricultural peak (Smith and Abruña, 1955; Pico, 1974). Development continued through the early 1900s and by the late 1940s, old-growth forest covered only ~6% of the entire island (Birdsey and Weaver, 1987).

Over the past 50 yr, the island's economy has changed from agrarian to industrial. Land use has shifted from cultivated cropland and pasture to a mixture of secondary-growth forest, pasture, and urban and suburban land uses. Forest cover has increased in the past 40 yr. A 1988 aerial survey of the Luquillo Town-

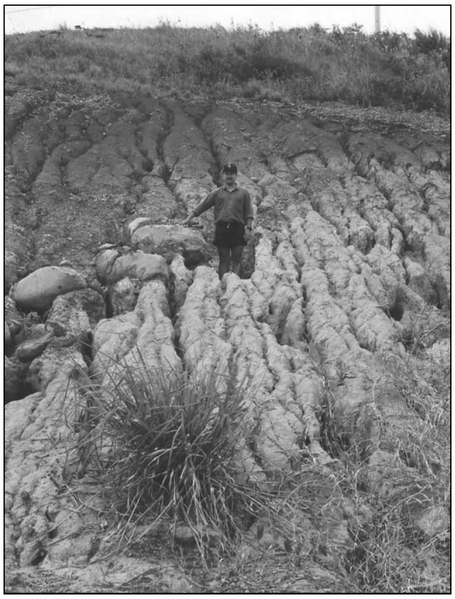

Figure 2. Deep gullies and rills formed within two years of clearing this hillside. Large, boulder-sized cores stones are evident and the base of the slope is littered with cobbles and gravel. Cultivation of slopes like these during the agricultural period would greatly increase the amount of coarse sediment supplied to the streams.

ship, which includes the Rio Sabana watershed and the eastern portion of the Rio Mameyes watershed, showed that approximately half of the total basin area has returned to forest (Thomlinson et al., 1997).

For the purpose of examining land-use impacts on river channels, the land-use history can be divided into four episodes. A pre-European period (prior to A.D. 1500) is characterized by extensive tracts of undisturbed forest. The settlement period (1500–1830) is marked by patchy clearance of lowland valley bottoms for subsistence agriculture and thinning of alluvial plain forests for timber and fuel. The most extensive clearance occurred during the agricultural period (1830–1950), when the alluvial lowlands were almost entirely planted in sugarcane and steep hillsides were cleared for subsistence agriculture, coffee, lumber, and fuel. The modern period (1950–present) is characterized by a conversion of cultivated cropland to pasture, forest, and urban land uses.

HISTORICAL TRENDS OF RUNOFF AND COARSE SEDIMENT SUPPLY

During the pre-European period, runoff was limited by rapid infiltration into thick forest soils on deeply weathered bedrock and undisturbed forest litter. Sediment supply was probably relatively small and sporadic, occurring primarily by mass wasting during large tropical storms (Simon and Guzman-Rios, 1990; Larsen and Torres Sánchez, 1992). Because Taíno agricultural activity probably occurred only in the low-gradient alluvial valleys and was limited to small, engineered patches, it likely had little effect on the supply of water and sediment to streams. During the settlement period, alluvial plain clearance for agriculture and settlement may have slightly increased the water and sediment supply. Fields plowed in fine-grained alluvium would be subject to erosion, but the low gradient of the alluvial plains would tend to limit it. Sediment yield would be composed primarily of fine-grained sediment that could be washed through the river system. There is no stratigraphic evidence to support either rapid aggradation or catastrophic stripping of flood plains during this period.

Widespread land clearance during the agricultural era would have dramatically increased both water and sediment supply. Forest removal on the clay-rich slopes would increase runoff through a decrease in interception, infiltration, and transpiration (Gumbs and Lindsay, 1982). Enhanced runoff on steep, cultivated slopes, lack of permanent vegetative cover, and the absence of soil conservation practices increase soil erosion (Gumbs and Lindsay, 1982; Tirado and Lugo-Lopez, 1984; Wahab et al., 1987) and sediment supply to streams. Because land clearance spread to steeper slopes, the proportion of coarse material in the sediment supply is likely to have increased through gullying and mass wasting. Aerial photographs taken in 1936 indicate that gullies had formed on many of the surrounding hillsides, scars of which are evident today. The effectiveness and rapid response of rill erosion and gullying was evident on a steep (20°) hillside cleared during the course of this study (Fig. 2). Within 2 yr, deep (>1.0 m) gullies formed and abundant cobbles and gravel were found at the base of the slope. Mass wasting, a major component of hillslope erosion in the Luquillo Experimental Forest, is also exacerbated by anthropogenic activities. For example, Larsen and Torres Sánchez (1992) showed that agricultural slopes (a combination of pasture and crop) were subject to twice as many landslides per square kilometer compared to forested slopes.

During the modern period, most hillside farms were abandoned, allowing establishment of secondary forest. Cultivated cropland decreased to 15% of total land area in 1964 and had nearly vanished by 1988. Most cropland was replaced by forest and residential development (Thomlinson et al., 1997). Increased runoff from urbanizing areas is balanced in part by decreased runoff from reforested areas, such that the net change in runoff may be small. Although Larsen (1991) showed that hillslope sediment supply is still active in the modern era, the amount is likely to have decreased substantially. Runoff from residential, pasture, and forest land all yield much less sediment than cropland. In addition, reforestation of steep upland areas stabilizes gullies as the amount of runoff supplied to them is reduced. Mass wasting is also likely to decrease as reforestation continues.

Although the absence of historical measurements prevents explicit estimates of water and sediment supply for the different eras, an index relating land-use change to water and sediment supply can be developed that provides a reference for evaluating relative changes in water and sediment during the different eras and a basis for comparison with other regions. An estimate of land use for the entire island at the end of the settlement period is provided by an 1828 forest inventory conducted by the Spanish (Birdsey and Weaver, 1987). Land use within the study area is available from an analysis of 1936, 1964, and 1988 aerial photographs from the Luquillo Township (Thomlinson et al., 1997). The land-use composition for each period (Table 2) is used to estimate the effect of land use on water runoff and sediment yield relative to an assumed presettlement state of complete forest cover.

Surface runoff for each land use is calculated relative to that from complete forest cover (Table 2) using the U.S. Soil Conservation Service curve number for each land use (Boccheciamp, 1977; Haan et al., 1994) and a 1 h rainfall of 75 mm (estimated recurrence interval of 2 yr; U.S. Weather Bureau, 1961). The average surface runoff ratio, weighted by percent cover for each land use in each era, provides an index of the change in runoff relative to the presettlement period. Runoff is estimated to increase relative to the undisturbed forest condition by 13% for the settlement period and 49% for the agricultural period. For the modern period, the relative runoff decreases slightly to 42% in 1964 to 32% in 1988.

The effect of land use on the relative rate of soil loss is estimated using the locally determined land-use cover factor from the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978; Mitchell and Bubenzer, 1980; Lal, 1990). Because we are considering the same area over time, other factors in the USLE remain constant, and the soil loss for each land use is calculated as a ratio of land-use cover factor relative to that from complete forest cover. Similar to the runoff estimate, the average soil loss ratio, weighted by the percent cover for each land use in each era, gives an index of soil loss for each period relative to the presettlement period. Soil loss is estimated to increase relative to the undisturbed condition by a factor of 4.3 for the settlement period and by a factor of 21 for the agricultural period. For the modern period, the soil loss relative to the undisturbed condition is a factor of 13 in 1964 and a factor of 1.6 in 1988. The estimated changes in soil loss are particularly sensitive to the cover factor for cropland, which is 70 times larger than that for complete forest cover (Table 2), making the computed soil loss highly sensitive to the estimated cropland area. However, even if the cropland cover factor for soil loss were reduced by an order of magnitude (an improbably small value for cleared land on such steep slopes), the soil loss during the agricultural era would be nearly four times that from forest cover and much larger than the estimated increase in runoff.

TABLE 2. LAND USE, RUNOFF, AND SOIL LOSS FOR THE DIFFERENT SETTLEMENT PERIODS

Land Use	Percent in each land use*					Runoff [ratio to surface runoff under complete forest cover]	Soil loss [ratio to loss under complete forest cover]
	Presettlement	Settlement	Agricultural	Modern			
		(1828)	(1936)	(1964)	(1988)		
Crop	0	4	27.3	15.8	0.0	2.0	70
Forest 20%–50%	0	10	10.3	5.1	8.3	1.4	3
Forest 50%–80%	0	10	6.2	4.6	1.7	1.2	2
Forest >80%	100	66	14.7	25.5	49.3	1.0	1
Pasture	0	10	40.8	43.2	21.5	1.4	3
Scattered urban	0	0	0.4	1.8	7.5	1.5	2
Dense urban	0	0	0.4	4.0	11.8	2.3	0
Runoff, as ratio to presettlement period (q_2/q_1)	1.00	1.13	1.49	1.42	1.31		
Soil loss, as ratio to presettlement period (q_{s2}/q_{s1})	1.00	4.26	20.9	12.9	1.57		

*Reference state is 100% forest cover during presettlement era. For each land use, change in runoff and soil loss relative to complete forest cover estimated using U.S. Department of Agriculture curve numbers and cover factors calibrated for Puerto Rico (Haan et al., 1994; Lal, 1990). For each era, change in runoff and soil loss relative to presettlement conditions calculated using average weighted by percent in each land use. 1828 land use from Spanish forest inventory (Wadsworth, 1950; Birdsey and Weaver, 1987). Land use in 1936, 1964, and 1988 from analysis of aerial photographs (Thomlinson et al., 1997).

A number of factors limit the accuracy of these estimates of runoff and soil loss, including uncertainty in the location and condition of cropland and application of runoff and soil loss parameters calibrated at the plot scale to a large area. Nonetheless, similar methods of estimating soil loss and runoff have been used successfully elsewhere (Knox, 1977; Jacobson and Coleman, 1986). Because of these uncertainties, however, we use these estimates only in a relative sense: changes in water supply relative to sediment supply and changes in both from one era to the next. Two central conclusions that may be drawn from these estimates—that runoff and soil loss both increased sharply during the agricultural era and that changes in soil loss were of a larger magnitude than those in runoff—are supported by independent lines of evidence.

The intensity of soil erosion during the agricultural era, particularly on steeper slopes, is supported by direct observations of widespread steepland erosion (Murphy, 1915; Simon and Guzman-Rios, 1990; Larsen, 1991; see also Fig. 2). The USLE method may actually underestimate soil loss during the agricultural period because the steep slopes cleared for agriculture would yield more sediment than low-gradient alluvial plains. The conclusion that the increase in sediment supply was larger than the increase in the water supply is supported by the simple observation that any increase in runoff is limited by the amount of precipitation. Soil erosion has no comparable limit in the availability of material. Furthermore, the scarred condition of the landscape during the agricultural period suggests that heavy soil erosion and abundant supply of both fine and coarse sediments occurred during the agricultural period.

To evaluate the influence of soil loss on stream channel change, consideration must be given to the caliber of the eroded sediment and the spatial distribution of its source area. An estimate of the spatial distribution of coarse sediment supply can be made using topography as a proxy for land use. Aerial photographs from 1936 show that most actively cultivated hillsides occurred on slopes of <30° and <200 m in elevation. Within that range, slopes >5° would likely yield the most coarse-grained sediment. Roughly 50% of the coarse-grained source area (i.e., between 5° and 30° and 0 and 200 m) is upstream of the study reaches in the Rio Mameyes and Rio Fajardo. The other half of that area is drained primarily by tributaries. In contrast, only 20% of the coarse-grained source area is found upstream of the study reach in the Rio Sabana. Because of the Rio Sabana's narrower basin, 80% of the coarse-grained source area comes from surrounding hillsides and tributaries. This suggests that a large portion of the bed material supplied to the Rio Mameyes and Rio Fajardo may have come from upstream, whereas most of the bed-material supply to the Rio Sabana would be laterally distributed along its course. Because of the shape of its basin, the Rio Sabana would likely exhibit a lower, but longer peak sediment supply compared to the Rio Mameyes and Rio Fajardo.

ALLUVIAL STRATIGRAPHY

Without direct measurement of previous channel conditions, the primary evidence for the initial, pre-European channel form is the preserved alluvial stratigraphy. Subsequent changes in channel form are inferred relative to a widely distributed pre-European stratigraphic boundary and from evaluation of along-stream variation in alluvial stratigraphy.

Alluvial stratigraphy was described along 12 valley sections on the Rio Mameyes, Rio Sabana, Rio Fajardo, and Rio Pitahaya, a major tributary to the Rio Sabana (Fig. 1). The sections were selected to cover a wide range of drainage area, valley slope, and bed material. All sections were alluvial and had well-developed flood plains or terraces. A channel-normal section was surveyed across the entire valley bottom. Cores were taken approximately every 10 m with a 90-cm-long, 2.9-cm-diameter soil punch and every 20 m with a 3.3-m-long, 5.7-cm-diameter bucket auger. The bucket auger penetrated thumb-sized gravel, but not cobbles, whereas the smaller soil punch penetrated pea-sized gravel. Descriptions of bank and core material were recorded in the field, noting degree of sorting, color, structure, mottling, organic debris, and/or anthropogenic deposits. Pebble counts were conducted within the channel portion of each transect using Leopold's (1970) method to characterize the size distribution of bed material. Some pebble counts were also performed on coarse bank material. In order to minimize sampling error and bias, all pebble counts were conducted by the same individual

TABLE 3. GENERAL CHARACTERISTICS OF RADIOCARBON SAMPLES

Location*	Lab number	Description	^{14}C age (yr B.P.)†	2σ maximum cal age (cal age intercepts) minimum cal age (cal. B.P.)§
Rio Fajardo (8.1km)**	N.A.	Silt cap soil	300 (±45)	481 (380) 164
Rio Fajardo (8.1km)**	N.A.	Mottled clay	8300 (±70)	9487 (9357) 9032
Rio Fajardo (8.3km)	AA-18119	Woody debris	1530 (±45)	1527 (1410) 1311
Rio Fajardo (8.3km)	Beta-63516	Woody debris	1320 (±70)	1346 (1267) 1064
Rio Fajardo (8.3km)	Beta-63517	Woody debris	1240 (±60)	1289 (1174) 9991
Rio Fajardo (8.3km)	Beta-63518	Woody debris	1320 (±60)	1330 (1267) 1088

Note: N.A.—not available.

*River and distance from ocean.

†Ages in bold were determined by accelerator mass spectrometry (AMS) at the National Science Foundation AMS facility in Tucson, Arizona; all others were determined by Beta Analytic using liquid scintillation techniques. Ages given in years before radiocarbon present.

§Radiocarbon ages (yr B.P.) were converted to calendar age (cal. B.P.) using Calib 4.1 by Stuiver and Reimer (1993) and calibration data from Stuiver and others (1998). Ages are given in calendar years before radio carbon present.

**Mellon et al. (1997).

using a template for particles <256 mm in diameter and a tape measure for those in excess of 256 mm. Woody debris and organic and cultural material were sampled for radiocarbon dating. All samples large enough to be dated were found within the alluvial plains of the Rio Fajardo. Six samples were dated using either standard or accelerator mass spectrometry (AMS) techniques (Table 3).

River sections in northeastern Puerto Rico typically have a compound form consisting of an active channel that is set within the steep walls of higher flood plains or terraces that extend hundreds of meters to the hillsides (Fig. 3). Typical cutbank stratigraphy and an inset gravel deposit, which is often found within the downstream reaches of the active channel, are shown in Figure 4.

The upper meter of alluvium is a light tan to brown loamy silt and silty clay. The top 20–30 cm of soil is a root layer beneath which are Fe-Mn concretions, mottles, and clay skins. The silt caps may be interbedded with thin (1–10 cm) lens of pebbles or sand that pinch out away from the channel. Isolated gravel and cobble grains were occasionally found buried in the silt cap at locations far from the present channel. These clasts and the lack of a buried preagricultural soil are probably the result of cultivation over the past few hundred years. The alluvial plains were cultivated before, during, and after the increase in sediment supply, suggesting that material from the preagricultural period up through modern times may have been mixed together. A radiocarbon sample from the silt cap was dated as 380 calendar years before radiocarbon present (^{14}C yr B.P.; Mellon, 1997), indicating that there was deposition during historic time. Although the original character of the pre-European surface is unknown, it is reasonable to presume that there was sufficient fine alluvial cover for farming (>20–30 cm minimum plow depth) when the Europeans arrived.

The silt cap is typically underlain by a 1–3-m-thick layer of cobbles and gravel set in a clast-supported brownish-tan sandy silt matrix. The cobble layer is interpreted as a laterally accreted deposit left by channel migration. Four samples from an organic lens overlying the cobble layer yielded ages between ca. 1100 and 1400 cal. B.P. (Table 3). The upper surface of the cobble layer typically extends across hundreds of meters of valley floor at nearly constant elevation, indicating that the riverbed was neither aggrading nor degrading while these cobbles were deposited. A stable bed elevation over this time scale suggests that the rivers would have been well adjusted to the prevailing water and sediment supply. The top of the cobbles is used in the following as a reference elevation for subsequent channel change.

The cobble layer is absent in some downstream sections in which the silt cap directly

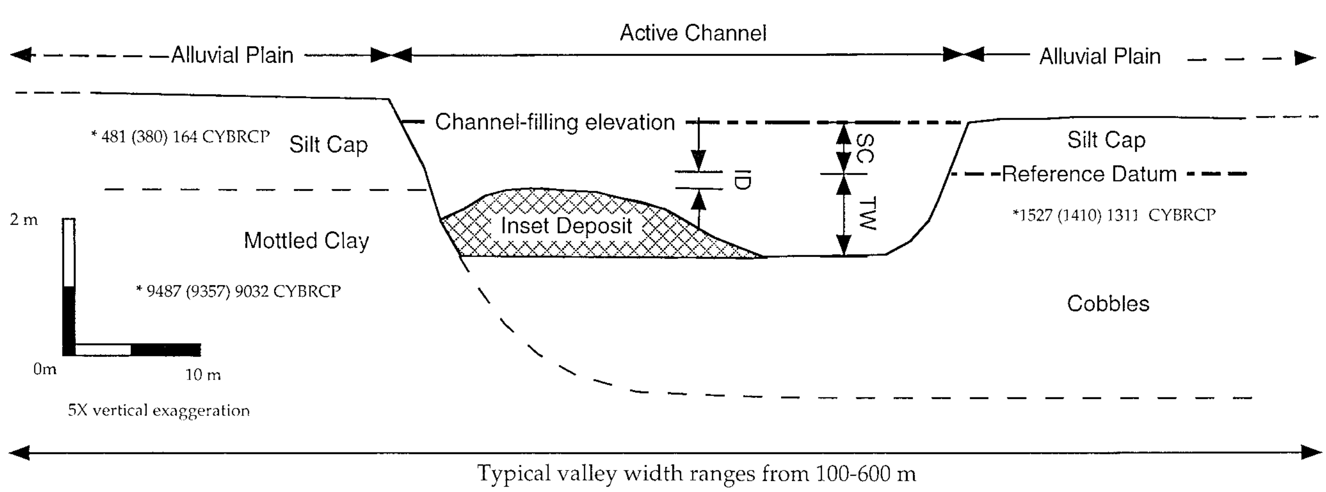

Figure 3. Schematic cross section showing main morphologic and sedimentologic features of northeastern Puerto Rican streams. Channels typically exhibit a compound form with a gravel deposit found within the channel. A silt cap overlies a cobble layer and a mottled clay layer where present. The top of the cobble layer is used as a reference datum to measure relative elevation between the thalweg (TW), silt cap (SC), and inset deposit (ID). The estimated cross-sectional area of the inset deposit is filled with a cross-hachured pattern. Channel dimensions were determined by using the top of the silt and cobble bank to define the channel-filling elevation. Representative radiocarbon sample locations are denoted by asterisks. Calendar years before radiocarbon present (cal. B.P.) are given in parentheses and two standard deviation confidence intervals are also shown (Table 3).

overlies a 9357 cal. B.P. (Mellon, 1997) heavily mottled clay. Ground elevation of these sections is generally at least 0.5 m higher than sections overlying the cobble layer and the silt cap tends to be slightly (<0.5 m) thicker. These higher silt caps grade downward through a diffuse, gradual contact with the mottled clays. Differences in elevation and age and the absence of laterally accreted coarse deposits suggest that these areas are remnants of a preexisting surface that was not reworked by lateral migration in the pre-European period.

Gravel deposits within the active channel are found on the inside of meander bends in some upstream reaches and become prevalent as longitudinal bars, midchannel bars, and point bars in downstream reaches. The insets are composed primarily of cobbles grading up to a gravel and sand surface. Vegetation can become established on the insets during extended periods without flooding. Fine sediment trapped by the vegetation can form a thin (<10 cm) silt cap, although their low elevation, lack of soil development, and small thickness suggest that the inset silt caps are transient features. The inset deposits are similar in sediment composition and appearance to the basal cobbles, although they differ in age, abundance of modern cultural debris, and topographic position.

Figure 4. A reach of the Rio Mameyes downstream of station 3200 illustrates the typical alluvial stratigraphy found along streams in northeast Puerto Rico. The cutbank to the left shows silts and clays overlying a fining-upward cobble layer, forming a silt cap. The cobble layer extends across the entire valley bottom in most cases, and is used as a reference datum. A partially vegetated inset gravel bar is seen on the right side of the picture. These deposits become larger and occur more frequently as one moves downstream.

ALONG-STREAM VARIATION IN CHANNEL GEOMETRY AND FLUVIAL STRATIGRAPHY

In the absence of historical information on channel condition, alternative approaches are needed to document channel change. One approach is to substitute space for time and compare a disturbed watershed to a similar watershed that is relatively undisturbed. The agricultural development in the study area was sufficiently extensive that no such comparisons can be found except for one small, undeveloped upland basin (drainage area 5.5 km^2). Comparing channels in this basin with two developed basins of comparable size (drainage areas of 4.6 km^2 and 7.5 km^2), but at lower elevation (Clark, 1997), we observe channel widths in the developed basins to be comparable to those in the undeveloped basin, but channel depth is 50% greater than in the undeveloped basin. If the undeveloped basin is indicative of pre-European conditions, then this space-for-time substitution suggests that developed headwater channels have degraded their beds relative to the pre-European channels. Although this may be indicative of land-use impacts for small headwater streams, there are no other undeveloped basins in the region for confirmation or extrapolation to larger basin sizes. As a result, the approach used here is to examine along-stream variations in channel geometry and sedimentation for evidence of river response to land-use change.

Channel width, depth, and area were measured from 75 surveyed cross sections at ~200 m spacing along alluvial portions of the three study rivers (Fig. 1). No cross sections were surveyed in the estuarine regions (~1200 m upstream along the Rio Mameyes and Rio Sabana and 2000 m upstream along the Rio Fajardo), where channel morphology may be affected by tidal fluctuations. To provide some control over local variation in channel geometry, sections were located at the riffle head or end of pool. Channel geometry was such that identification of the channel margin was typically unambiguous; the elevation of the top of the channel is defined as the top of the adjacent overbank surface (Fig. 3). Channel area was measured from plotted cross sections and average channel depth was calculated as area divided by channel width.

In all cases, the river channels show either no along-stream trend in size or a distinct decrease in channel size in the downstream direction (Fig. 5). The case is clearest for the Rio Sabana, where a weak downstream decrease in channel width and a strong downstream decrease in channel depth produce a consistent downstream decrease in channel area. Similar trends are evident on the Rio Mameyes, although the scatter is somewhat greater. On the Rio Fajardo, there is no distinct downstream variation in channel geometry.

A downstream decrease in channel depth may result from several causes, including upstream bed scour, downstream bed aggradation, or a downstream decrease in bank elevation. An indication of the relative influence of these different topographic elements is gained by plotting the elevation of the bed, inset, and bank top relative to the top of the cobble layer. The cobble layer provides a consistent local datum because its nearly constant elevation across entire valley sections suggests that it was deposited during a stable period. Furthermore, the alluvial plains that overlie the cobbles have been actively formed throughout the agricultural and modern eras, such that historic overbank deposition is recorded. Using the top of the cobble layer as a reference, the relative elevations of the bank top, the top of the inset deposit, and the thalweg were determined as shown in Figure 3 and are plotted against downstream distance in Figure 6 for the 21 sections for which the elevation of the cobble layer is available.

The downstream trends in the relative elevation of all topographic surfaces either increase or remain relatively flat, suggesting neutral to aggradational conditions as one proceeds downstream. The clearest trends are found in the thalweg and inset on Rio Sabana and Rio Mameyes, which show a consistent increase in elevation relative to the cobble layer (Fig. 6), suggesting possible upstream degradation and/or downstream aggradation of the river bed. The elevation of the inset deposits relative to the cobble layer also suggests aggradation in the lower reaches. Whereas the inset is 1–2 m below the top of the cobble layer in upstream reaches, the inset elevation

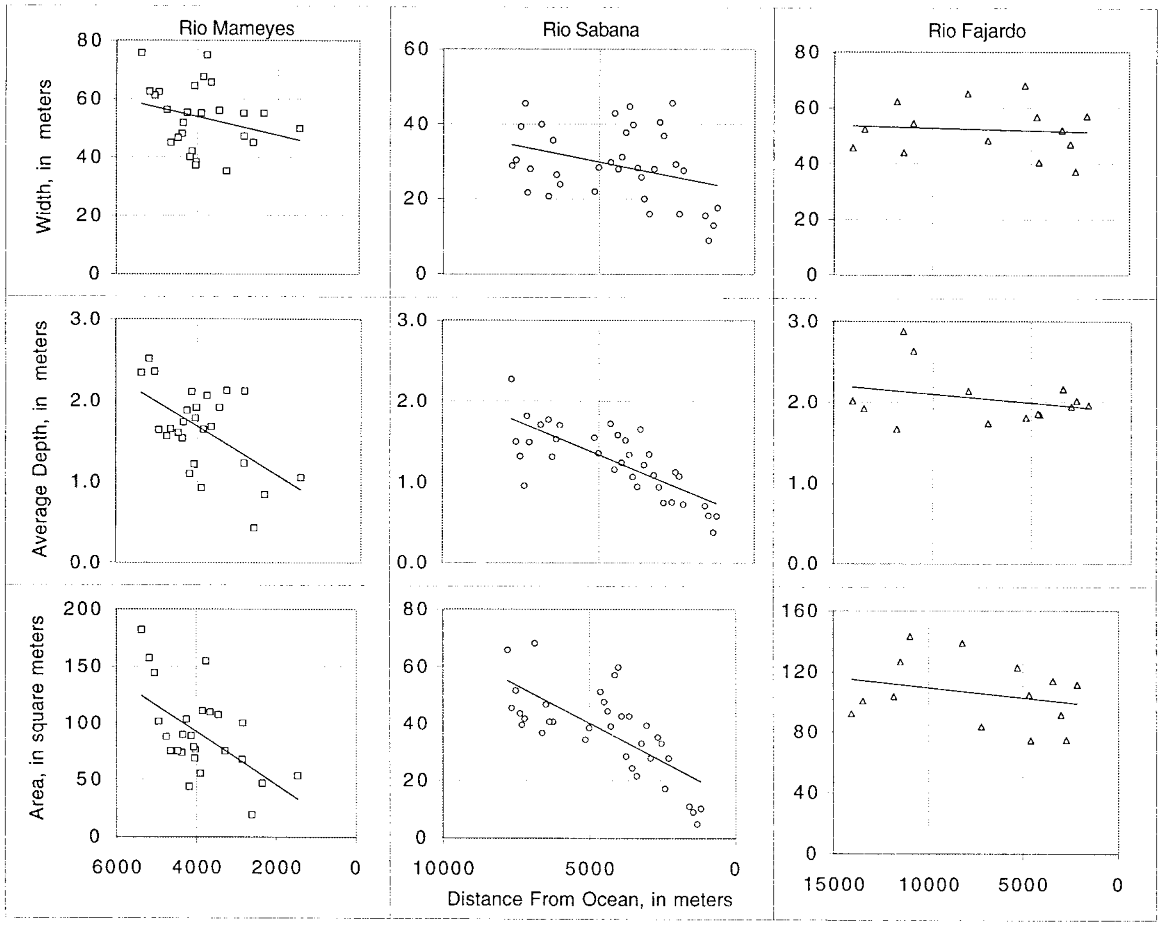

Figure 5. Downstream trends in channel geometry for alluvial sections of the Rio Mameyes, Rio Sabana, and Rio Fajardo. No sections were measured in estuarine portions of these streams or in a bedrock-controlled reach between stations 5100 and 6000 on the Rio Sabana. The Rio Mameyes and Rio Sabana show a distinct decrease in channel size in the downstream direction, whereas there is no significant along-stream trend in channel size for the Rio Fajardo. Note different scales used in each panel.

approaches that of the cobble layer in the lower Rio Mameyes and exceeds the cobble layer elevation in the lower Rio Sabana, strongly suggesting bed aggradation in the downstream most reaches. Although the data are limited, the overall trend in relative elevations suggests increasing channel aggradation in the downstream direction. Trends in the bank top elevation are also positive, although the slopes of the trend lines are near zero and the correlation is poor, indicating that most of the downstream decrease in channel depth is related to relative changes in bed elevation.

Any downstream pattern of bed aggradation may also be evident using an estimate of the frequency and volume of inset deposits. At each cross section with inset deposits, the volume of the inset was estimated by taking the thalweg as the base of the deposit and calculating the resultant area (cross-hachured area in Fig. 3). This is expressed as a ratio of inset area to the present channel cross-sectional area and is shown in Figure 7. The relative size of inset deposits increases in the downstream direction along all three rivers, with a particularly rapid increase in the lower 16% of the Rio Mameyes and Rio Sabana. Information on the lower Rio Fajardo is not available because any inset deposits have been disturbed or removed by dredging.

Because there is no evidence that these rivers lose discharge, a pattern of decreasing flow depth and relative channel aggradation in the lower reaches should be evident in the alongstream variation in the magnitude and frequency of flows that fill the channels. This discharge was estimated for each measured cross section using Manning's equation and a field estimate of the roughness coefficient based on sediment size and channel characteristics (Cowan, 1956; Limerinos, 1970). Discharge capacity for the full channel cross-section decreases in the downstream direction along all three rivers (Fig. 8). The combination of channel slope, area, and hydraulic radius decreases faster downstream than the hydraulic roughness, resulting in smaller downstream channel-filling discharge.

To provide an indication of the frequency of flows that fill the channel, the 1.5, 2, and 5 yr discharges for the Rio Sabana and Rio Fajardo were estimated using regional discharge versus drainage area relations calibrated for 9 gages in the region (Table 1; Clark, 1997). Because the gages have similar land-use histories and come from the same physiographic and climatic province, the variation of discharge with drainage area can be described over a wide range of drainage areas (Table 1). This allows estimation of the 1.5, 2, and 5 yr recurrence interval discharges throughout the entire Rio Sabana and Rio Fajardo watersheds. A specific discharge versus drainage area relation was developed for the Rio Mameyes using the discharge records for

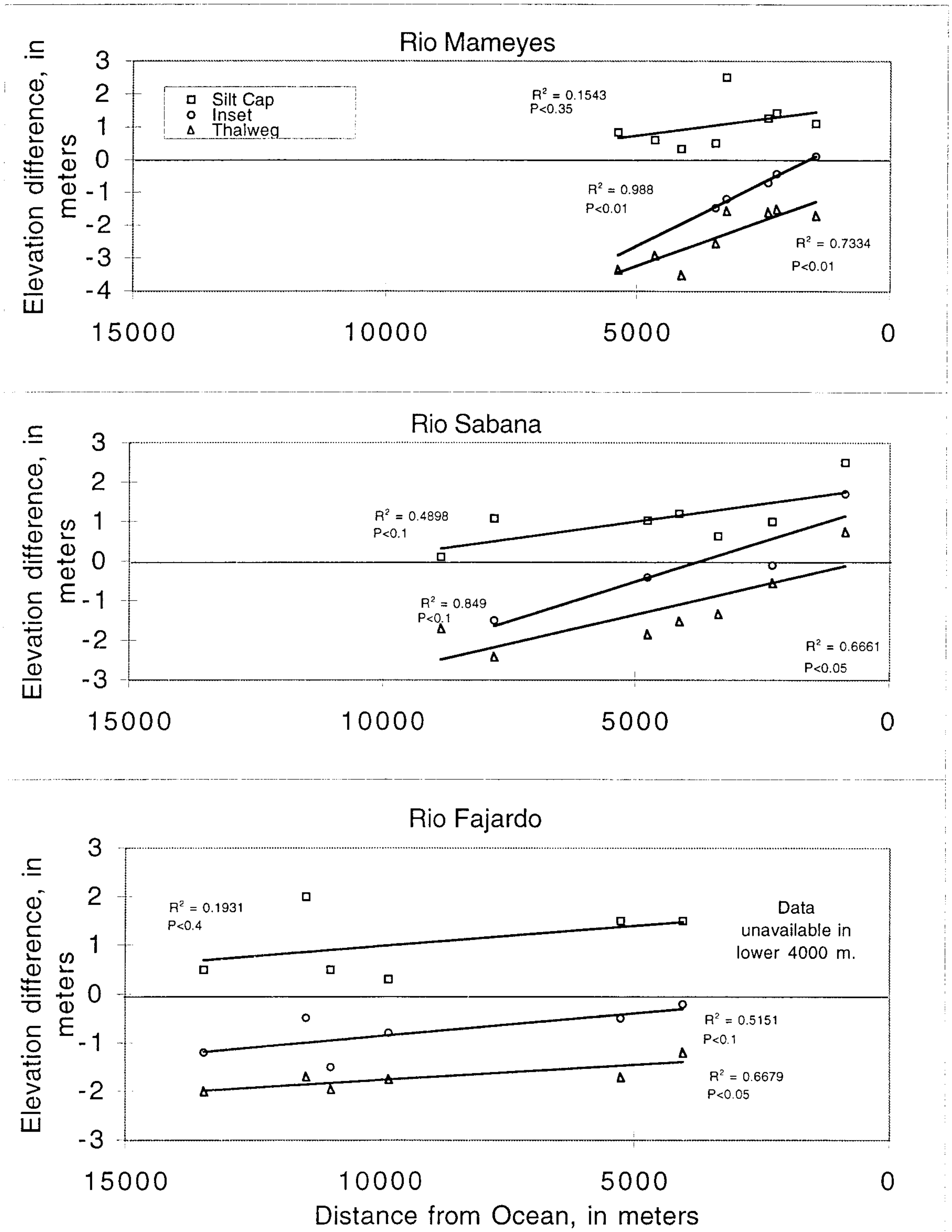

Figure 6. Downstream trend in the top of the thalweg, silt cap, and inset deposit elevation relative to the top of the cobble layer found in the banks of alluvial sections of the Rio Mameyes, Rio Sabana, and Rio Fajardo. In all cases the top of the cobble layer is plotted at an arbitrary elevation of 0. The ordinate is the difference between the elevation of the top of the cobble layer and the tops of the other units. Only cross sections for which the cobble layer was surveyed were included. Both the top of the inset deposits and the thalweg increase in relative elevation in the downstream direction. The silt cap exhibits a weak, but statistically insignificant increase in relative elevation (thickness) as well. Note different scales used on each ordinate axis.

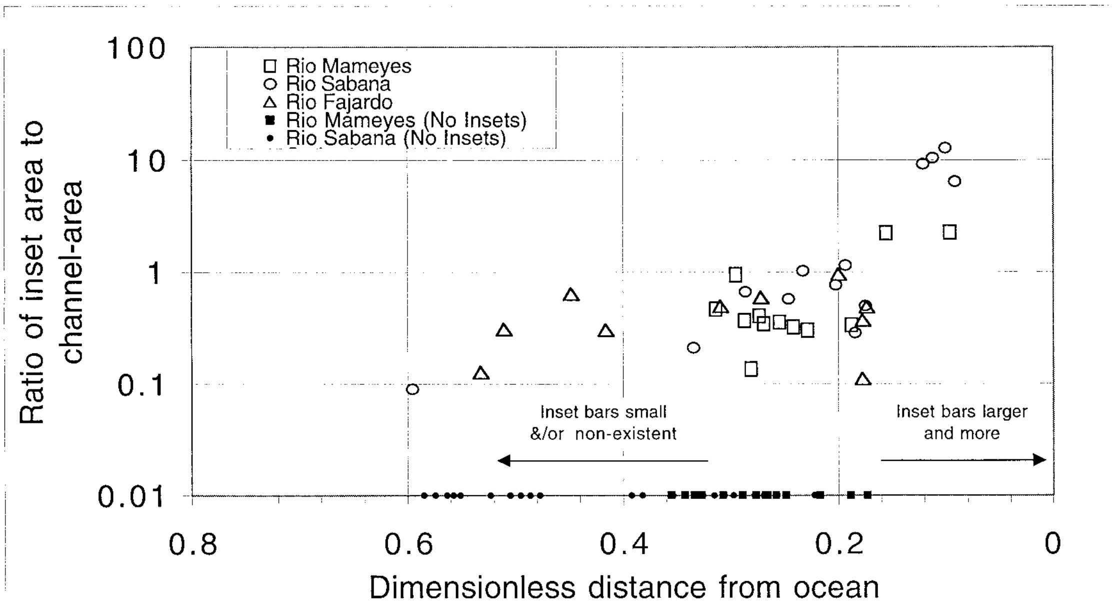

Figure 7. Downstream trend in the ratio of channel area occupied by inset deposits relative to present channel-filling flow area for alluvial sections of the Rio Mameyes, Rio Sabana, and Rio Fajardo. Downstream distance has been normalized by total river length (U.S. Geological Survey blue line). Cross sections without inset deposits are shown as filled symbols. At a dimensionless distance >0.32, the number of inset deposits decreases. No insets were observed in the lower 0.18 of the Rio Fajardo due to recent channel dredging. The relative size of the inset deposits increases on the Rio Mameyes and Rio Sabana in the last 0.16 of dimensionless distance.

the period during which two gages were operated on this stream.

Recurrence intervals for channel-filling flow in upstream sections are between 2 and 5 yr and decrease in the downstream direction for all three rivers (Fig. 8). The channel-filling recurrence interval for downstream sections on the Rio Fajardo is about 1.5 yr, whereas the channel-filling recurrence interval for downstream sections on the Rio Mameyes and Rio Sabana is much smaller than 1.5 yr. Field observations and eyewitness accounts support the conclusion that downstream channels flood even more frequently. For example, the Rio Mameyes gage located at station 3200 has undergone channel capacity flow 17 times in as many years. Both the downstream decrease in magnitude of channel-filling discharge and the very high frequency of overbank flow in the downstream reaches provide further evidence that they have aggraded.

The larger channel size and longer recurrence interval for channel-filling floods in the upstream sections, together with the absence of inset deposits and the low thalweg elevation relative to the reference datum, suggest that agricultural period sediment has been evacuated from these reaches and that elevated runoff in the modern period has produced bed degradation relative to pre-European conditions. Downstream reaches are evidently undersized based on the recurrence interval of modern bankfull flow. The channel-filling flow of 20 m^3/s estimated for the downstream reaches of the Rio Sabana (Fig. 8) is remarkably small for a watershed of its size, suggesting that these lower reaches are filled with sediment relative to their pre-European condition. This aggradation is largely in the form of channel bars (inset deposits) that have partially filled the channel. The inset deposits become higher in relative elevation, larger, and occur more frequently in the downstream direction (Figs. 7 and 8). Taken together, these along-stream patterns suggest that the coarse agricultural era sediment has been partially removed from the river channels, preceding from upstream to downstream (Jacobson, 1995), and that future channel adjustments in response to the present supply of water and sediment will involve erosion of bed material now stored in the downstream reaches.

DISCUSSION

Channel Response to Changes in Discharge and Coarse Sediment Supply

Channel response to changes in water and sediment supply can take a variety of forms, including changes in width, depth, and planform geometry. Explicit prediction of the full suite of these changes is prohibited by the absence of a general fluvial morphology model, particularly a bank erosion component, as well as by the absence of most of the necessary initial and boundary conditions needed for such a prediction. Nonetheless, an approximate expression for channel change, consistent with the approximate nature of data typically available, is useful for indicating the direction of change and the relative influence of changes in water and sediment supply. Among the best known are Lane's (1955) illustration of channel aggradation or scour in response to changes in water and sediment supply and Schumm's (1969) qualitative relations for river metamorphosis. An explicit relation developed by Henderson (1966, p. 449) provides a useful basis for examining channel change. Using Brown's (1950) approximation of the Einstein bedload equation and the steady uniform form of the momentum relation (depth-slope product), Henderson developed a proportionality between sediment transport rate per unit channel width q_s, hydraulic radius R, bed slope S, and sediment caliber D:

$$q_s \propto \frac{R^3 S^3}{D^{3/2}} \tag{1}$$

Assuming that the Chézy flow resistance

coefficient C is constant, the water discharge per unit width q is proportional to R and S as

$$q \propto R^{3/2}S^{1/2} \tag{2}$$

Solving equation 2 for R and substituting into equation 1 yields an equation relating q_s to q, S, and D:

$$q_s \propto \frac{q^2S^2}{D^{3/2}} \tag{3}$$

(Henderson, 1966, p. 449). This relation is a specific form of the elementary proportionality,

$$q_sD \propto qS \tag{4}$$

proposed by Lane (1955) to describe channel scour and aggradation. Although equation 3 is clearly an approximation, it provides a basis for evaluating the relative influence of the individual variables. Other reasonable assumptions (e.g., a different transport or flow resistance relation, or variable hydraulic roughness) would slightly alter equation 3, although these difference are likely to be unimportant in the context of an approximate analysis of channel response to historical changes in water and sediment supply. It is useful to write equation 3 for two different time periods and take their ratio:

$$\frac{q_{s1}}{q_{s2}} = \left(\frac{q_1}{q_2}\right)^2\left(\frac{S_1}{S_2}\right)^2\left(\frac{D_2}{D_1}\right)^{3/2} \tag{5}$$

which has the benefit that terms not explicitly included in equation 3, such as water and sediment density, cancel. Equation 5 may be interpreted as a ratio of transport rates predicted for two different combinations of q, S, and D. For the purpose of evaluating channel change, however, it is more useful to interpret the left side of equation 5 as a ratio of sediment supply and the right side as a ratio of transport capacity. If the rate of sediment supply to a reach is changed, equation 5 indicates the combination of q, S, and D that will produce the equivalent change in transport capacity. For example, if the rate of sediment supplied is doubled from period 1 to period 2, equation 5 indicates that increasing q by a factor of 1.41, or decreasing D by a factor of 1.59, would increase in transport capacity just enough to carry the increased sediment load.

If a change in water and sediment supply results in a new transport capacity that is smaller than the new sediment supply, the bed will tend to aggrade; if the new transport capacity exceeds the sediment supply, the channel will scour. By sediment mass conservation, aggradation will tend to increase S, whereas degradation will decrease S. Grouping the variables representing water and sediment supply, equation 5 becomes

$$\frac{S_2}{S_1} = \frac{q_1}{q_2}\left(\frac{q_{s2}}{q_{s1}}\right)^{1/2}\left(\frac{D_2}{D_1}\right)^{3/4} \tag{6}$$

A value <1 on the right side of equation 6 indicates a tendency toward bed scour and a value >1 indicates a tendency for bed aggradation. Equation 6 cannot be interpreted too closely, because a wide range of information is excluded from the analysis, including changes in channel width and planform, sediment sorting, and fluctuations and correlation in water and sediment supply. Nonetheless,

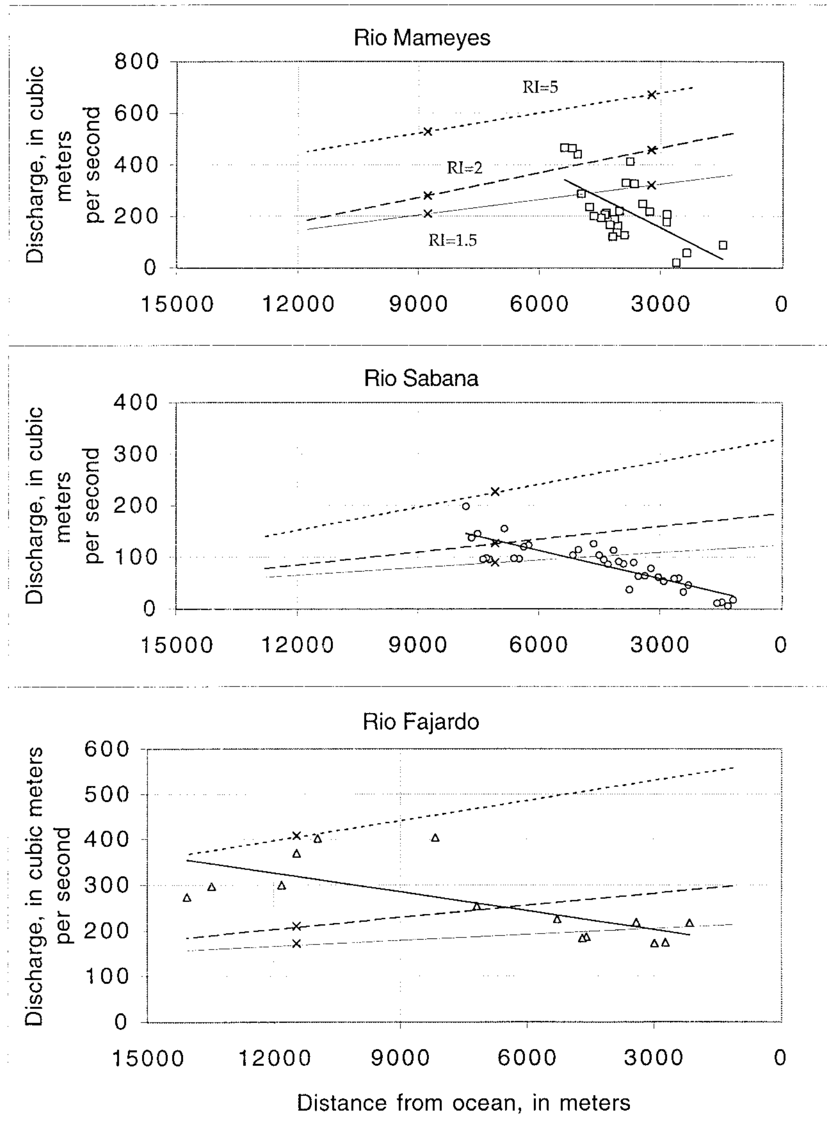

Figure 8. Downstream trend in channel-filling discharge for alluvial sections of the Rio Mameyes, Rio Sabana, and Rio Fajardo. Locations of U.S. Geological Survey gages are denoted by x. The 1.5, 2, and 5 yr recurrence interval flows are shown as solid, long dashed, and short dashed lines, respectively. The slopes of the lines for the Rio Sabana and Rio Fajardo were determined by regional drainage area vs. discharge relationships from 9 gages in and around the study area (Table 1). The lines for the Rio Mameyes were determined using the two gages located on that river. In each case, the channel-filling discharge decreases and occurs more frequently as one moves downstream. Note different scales used on each ordinate axis.

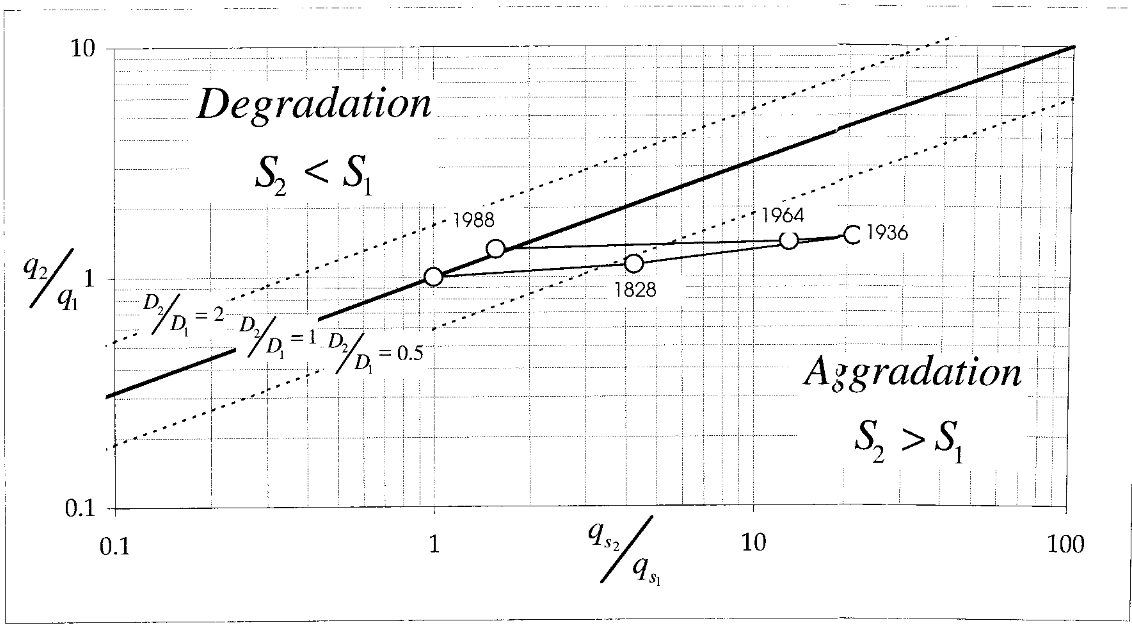

Figure 9. Likely channel response (scour or aggradation) to changes in water and sediment supply from t_1 to t_2. The solid line represents the solution of equation 6 for no change in the grain size of the sediment supply ($D_2/D_1 = 1$). Solutions are also shown for a factor of two change in grain size. Channels falling below or to the right of the line would tend to steepen through preferential deposition; the slope of channels above and to the left of the line would decrease through preferential scour. Approximate water and sediment supply for different periods in northeast Puerto Rico (Table 2) suggest a sequence of aggradation followed by degradation.

the relation provides a useful index of the tendency toward scour or aggradation and provides an explicit form (relative to equation 4) defining the relative influence of changes in discharge, sediment discharge, and grain size.

The water and sediment supply variables in equation 6 may be represented as a family of curves of constant D_2/D_1 on a plot of q_2/q_1 against q_{s2}/q_{s1} (Fig. 9). Combinations of these variables that produce a value >1 in equation 6 fall to the right of the bold line and indicate a tendency toward bed aggradation ($S_2 > S_1$). Channel slope can also increase through a decrease in sinuosity. Because the channel margins of our study rivers are cohesive and apparently resistant to erosion, it is likely that the immediate channel slope adjustment will be primarily through bed aggradation. This assumption is supported by our comparison of developed and undeveloped headwater basins in which similar widths were observed regardless of basin land-use history.

The likely response of northeastern Puerto Rican rivers to changes in water and sediment supply over the last 200 yr is indicated by using estimated values of q_2/q_1 against q_{s2}/q_{s1} (Table 2). The starting point is the pre-European condition of complete forest cover, which was used as the reference case for the water and sediment supply ratios. During the settlement period (1828), sediment supply exceeded transport capacity—a trend continued in the agricultural period (1936), where sediment supply was much greater than transport capacity, indicating aggradation of the streambed. Channel aggradation is also indicated by a presumed coarsening of sediment supply during the agricultural period. A coarsening of sediment supply causes the equilibrium line to shift to the left, putting the agricultural period water and sediment supply even further into the aggradational zone. The modern period is represented by a large decrease in sediment supply, particularly after 1964, and a smaller reduction in water supply, so that the capacity and supply ratios in equation 6 are nearly balanced (Fig. 9). The relation indicates that the modern channels will likely degrade their beds relative to the agricultural age channels, but gives little guidance concerning future channel form relative to the pre-European channel.

Because discharge in the modern period is larger than that in the undisturbed state, channels adjusted to modern flows will presumably be larger than undisturbed channels. The large flow depth, absence of inset deposits, and low relative elevation of the bed observed in the upstream reaches suggest that the medium-term (century) response is a deepening of the channel through bed scour. This conclusion is further supported by the observation of larger channel depths in the direct comparison of two small, disturbed watersheds with a small upland watershed of similar drainage area. It is not known whether these channels may eventually widen, e.g., during an extreme flood capable of removing bank vegetation, or through gradual lateral migration of the river channel.

Reverse Channel Morphology

The downstream decrease in channel depth and cross-sectional area that we observe is counter to the normal expectations, particularly in rivers that do not lose discharge along their course. Such trends have not been commonly addressed in the literature, even though the land-use history to which we assign responsibility is quite common, particularly in areas of European colonial development. This leads us to ask whether this pattern of downstream-shrinking channels, which we term reverse channel morphology, is rare or, for some reason, rarely observed.

Although explicit discussion of contemporaneous downstream decrease in channel area is relatively rare, there are a number of observations of channel response to agricultural land use that are consistent with what we observe in northeastern Puerto Rico. In the Piedmont region of the eastern United States, where both the nature and timing of land-use changes are similar to northeastern Puerto Rico (Trimble, 1974; Jacobson and Coleman, 1987), Ruhlman and Nutter (1999) demonstrated widespread channel enlargement throughout the upper and middle reaches of the Upper Oconee River basin, Georgia. Channel enlargement progressed such that first- to third-order streams had overbank recurrence intervals ranging from <2 yr to <500 yr (most exceeded 2 yr), whereas recurrence intervals of overbank flow in higher order streams were usually <2 yr. The slope of the channel capacity discharge versus drainage area trend is near zero and is statistically insignificant, indicating that channel capacities do not change much over an order of magnitude increase in drainage area. Gradual removal of agricultural sediment stored in the upstream reaches is presumed to result in these unusual along-stream trends in channel morphology and flood frequency.

Although downstream channel morphology has not been reported for other streams in the Piedmont, unusual trends in flood frequency have been described. Costa (1975) observed that Piedmont basins with drainage areas <26 km^2 have longer bankfull recurrence intervals than larger basins, suggesting that upstream reaches may be relatively enlarged. Kilpatrick and Barnes (1964) noted that, in general, Piedmont streams with flatter slopes have shorter bankfull recurrence intervals than steeper gradient streams, which further suggests that smaller, steeper headwater streams have had much of the stored agricultural sediment removed (Costa, 1975).

The Driftless area of southwestern Wisconsin also has a land-use history similar to northeastern Puerto Rico (Knox, 1977; Trimble and Lund, 1982). Intensive agricultural land use extended into the early 1970s in the Platte River watershed (Knox, 1977). If bankfull width is defined as that corresponding to the 1–2 yr flood, width generally increases downstream, although the correlation is poor and the slope of the trend is near zero. If, however, the actual channel-filling width is considered, width is observed to decrease in the downstream direction (Knox, 1999, personal commun.). Moreover, Knox (1977) determined that the recurrence interval of channel-filling discharge in tributary reaches exceeded 100 yr, whereas downstream reaches flooded annually. Similar to northeastern Puerto Rico, the alluvial plains in upstream reaches are rarely inundated, leaving flood plains formed before and during the agricultural period as terraces (Knox, 1987; Knox and Hudson, 1995). Channels have incised in steep headwater tributaries where not on bedrock, but elsewhere incision has not occurred because of channel-bed armoring with cobble and boulder gravels (Knox, 1999, personal commun.). However, the hydraulic depths of southwestern Wisconsin channels have increased greatly in the downstream direction because bank heights have increased dramatically through overbank sedimentation.

Trimble and Lund (1982) used channel surveys and cross-valley core stratigraphy to demonstrate several meters of vertical accretion in the downstream alluvial portion of the Coon Creek basin, Wisconsin. Sediment supply in this basin began to decrease sharply with the advent of soil conservation practices, and Trimble and Lund (1982) described a downstream migrating wave of sediment, much of which remains within the basin. The upstream most channel of seven published cross sections widened and scoured its bed between 1938 and 1976 and is the largest of the seven channels. The remaining downstream channels have continued to aggrade over this period and show a weak downstream decrease in depth and virtually no downstream change in width.

In some cases, a similar along-stream channel pattern has been observed in response to controls different from those in northeastern Puerto Rico. Nanson and Young (1981) found channel width to decrease in the downstream direction where a decrease in valley slope and stream power is accompanied by a wide flood plain and an aggressive grass species capable of trapping sediment and producing progressive channel narrowing. Both the mechanism and the form of channel change are different from that occurring in northeastern Puerto Rico. Ebisemiju (1989) observed that the downstream change of flow depth was not demonstrably different from zero for three basins with urbanizing headwaters and intensive agriculture in the lowlands. Although the pattern of channel change is similar, if less extreme, than that observed in northeastern Puerto Rico, the land-use pattern producing the changes is different.

An important contributing factor helping to explain the downstream morphological response to land-use–derived sediment must be the caliber of the sediment. If the increased sediment supply is predominantly fine grained, as supposed for agricultural erosion in the Maryland Piedmont and Wisconsin Driftless area, much of the additional sediment may wash directly through the stream system and deposition is likely to be focused on the flood plain (Jacobson and Coleman, 1987; Knox, 1987). Only extreme increases in fine sediment supply are likely to produce bed aggradation (Trimble, 1974; Trimble and Lund, 1982; Jacobson and Coleman, 1987). Fine-grained overbank deposition will tend to cause bank heights and channel depths to increase, a trend opposite to the decreasing depths produced by bed aggradation. If the increased sediment load includes a substantial portion of coarse bed material, the time required to evacuate the majority of this sediment will be much longer and sedimentation will focus on bed aggradation and storage in channel bars. The occurrence of abundant bed material in northeastern Puerto Rico is suggested by the coarse caliber of the in-channel deposits, which are traceable to gullies on the steep slopes cleared during the agricultural period. Incomplete upstream to downstream evacuation of this sediment would lead to the situation we hypothesize for northeastern Puerto Rico, wherein the downstream reaches remain aggraded and shallow. Regardless of the caliber of sediment supplied, a decrease in sediment supply will initiate a progressive upstream to downstream erosion and removal of the bed material, producing a downstream decrease in channel depth until all of the excess sediment is transported out of the system.

Our interpretation of downstream shallowing produced by incomplete evacuation of coarse sediment from an earlier era may have useful implications. In regions with a historical period of steepland erosion, a downstream decrease in channel size may indicate incomplete evacuation of a previous oversupply of coarse sediment, suggesting that future channel change in the lower reaches will include degradation as competent flows enlarge the channel to accommodate the modern water and sediment supply.

Another source of comparison for our observations of along-stream changes in channel geometry is the extensive literature on hydraulic geometry, originating with the seminal work of Leopold and Maddock (1953). Because we determined channel dimensions that correspond to a flow that fills the channel, rather than a flow of constant frequency, our along-stream morphology observations cannot be directly compared to those obtained with the latter, classical approach. It is interesting, nonetheless, to note that the reverse channel morphology we observe would generally not be evident using classical downstream hydraulic geometry for a discharge of a constant frequency. Wherever discharge magnitude increases in the downstream direction, channel area will tend to increase by the requirements of flow continuity and flow resistance, mediated only by a downstream decrease in roughness, which would be sufficient to counteract downstream increases in discharge in only unusual circumstances. Hence, a downstream increase in channel size for a given flow frequency is nearly a requirement of classical hydraulic geometry, even in cases where the full bank top to bank top river channel decreases in size in the downstream direction.

Another difference between our work and that of many classical hydraulic geometry studies is that we examine channel morphology along individual watercourses, whereas most downstream hydraulic geometry results are compilations from different streams. When hydraulic geometry observations for different streams are combined, even when they are located within a single region, single-watercourse hydraulic geometry trends that differ from the regional average may appear only as scatter within the overall data set. Consistently different single-stream trends would not necessarily be evident in a regional compilation. For example, Fox (1974) examined channel sections throughout the 965 km^2 watershed of the Patuxent River, Maryland, and found that downstream hydraulic geometry relations for width and depth fell within normal bounds, both increasing downstream. If the data are grouped by watercourse, however, no downstream trend in depth is evident in two of three cases with at least six sections. In the case where width and depth increase downstream, the river passes through a rapidly urbanized area developed with little stormwater control, such that urban runoff would likely have enhanced a downstream increase in channel size.

Downstream hydraulic geometry trends are generally not used to forecast channel change, in part because of the scatter involved. It appears, however, that changes in channel geometry along an individual watercourse may provide a useful index for evaluating channel history and forecasting channel change. In northeastern Puerto Rico, the downstream decrease in channel size and downstream increase in stored coarse bed material, when coupled with the watershed history over the past two centuries, suggest that future channel change is likely to involve gradual removal of bed material in the downstream reaches, accompanied by an increase in channel depth and a decrease in overbank flooding. In this sense, downstream channel morphology provides useful information for planning and river management, not through specification of channel size from an empirical trend, but by identifying the nature and location of future channel change.

CONCLUSIONS

More than a century of intense agriculture in northeastern Puerto Rico produced a large increase in the amount of water and sediment supplied to the region's streams. Land clearance extended to steep hillsides, producing abundant gullying and mass wasting, such that the sediment supply included a much larger component of coarse bed material than in earlier or later periods. In the past 50 yr, land use has shifted to forest, suburban, and industrial use, sharply reducing sediment supply and producing a smaller decrease in water supply. These changes in water and sediment supply are likely to have had a significant impact on river channels in the region, although little historical information is available to directly evaluate the channel response.

Channel depth decreases in the downstream direction along these channels. Because channel width is relatively constant, channel area also decreases in the downstream direction. Downstream decreasing channel area is accompanied by a decrease in the recurrence interval of channel-filling flow from more than two years in the upstream reaches to several times per year in the downstream reaches. The thickness of fine-grained overbank deposits is relatively constant along the channels and the along-stream variation in depth is caused by upstream channel degradation and storage of coarse bed material in downstream reaches. The elevation of the modern channel thalweg and bar top rises relative to an earlier gravel bar deposit within the alluvial plains, further suggesting that the downstream variation in channel geometry is related to a downstream increase in stored bed material.

The downstream trends in channel geometry and channel sedimentation may be explained by an incomplete removal of excess coarse sediment supplied to the river during the period of intensive agriculture. As the bed material has been gradually evacuated from upstream to downstream during the modern period, the trend of downstream decreasing channel depth is presumed to represent a transient state. Continued transport is likely to lead to degradation of the bed in downstream sections, as the channel adjusts to the modern supply of water and sediment

Reverse (downstream decreasing) channel morphology is likely when excess coarse sediment from an earlier period has not been completely evacuated from the stream system. Although there is evidence of compatible channel adjustments in areas with similar land-use history, the small number of reported observations may be attributed in part to multiwatershed compilations, in which contrary trends along individual watercourses are obscured by scatter in regional relations. Downstream reduction in channel area along individual streams in areas with similar land-use history implies channel disequilibrium and anticipates particular channel adjustments. Variation of channel geometry along a single watercourse provides an objective basis for identifying the nature and location of future channel change.

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