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Morphology and sedimentation in Caribbean montane streams: examples from Jamaica and Puerto Rico

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ABSTRACT

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This paper presents a summary description of the morphology, sedimentation, and behaviour of the montane streams of eastern Jamaica and eastern Puerto Rico. The area is located within a 200 km wide seismically active zone of Neogene left-lateral strike-slip deformation which defines the plate boundary between the Caribbean and North American Plates. Tropical storms, occasionally strengthening up to hurricane force, affect the region periodically. This is an area of steep, mass-movement-scarred hillslopes which supply a large amount of coarse sediment to the rivers. From the description presented, we have constructed a model for the rivers of this region controlled by both neotectonics and periodic large floods.

The drainage density is low with a near-rectangular stream network. The gradients are steep with boulder accumulations in the channels, their location at times related to the presence of large past landslides on hillslopes. Narrow, steep and confined channels occur in the mountains, but in wider sections and lower down near coastal plains, flood depositional forms appear in coarse valley alluvium. Small-scale deviations from the general pattern occur locally, controlled by variations in lithology, neotectonism, seasonality in flow, etc. This model for Caribbean montane streams differs considerably from the standard descriptions of alluvial rivers for which a number of detailed studies are available.

Introduction

The montane streams of the Greater Antilles group of Caribbean islands share several morphological characteristics. In their headwaters, they flow in narrow valleys, have steep gradients, and transport and deposit coarse sediment including boulders. At lower elevations, multiple channels and depositional surfaces occur at various levels within the valley floor. In this paper we suggest that such characteristic forms and behaviour occur regionally due to the combination of several geographical factors. Located near the northern boundary of the Caribbean Plate between 17°30′N and 23°15′N latitudes, this is an area of geologically controlled valley alignments, steep hillsides, frequent mass movements, high annual precipitation, and periodic short-duration high-magnitude rainfall from various types of tropical storms which may reach hurricane force. The location is the prime factor behind the form and behaviour of the channels.

The standard geomorphic and sedimentological models were not designed for such streams. Here we present a conceptual model for stream morphology, sedimentation, and behaviour, using examples from the streams of the Blue Mountains of eastern Jamaica and the Luquillo Moun-

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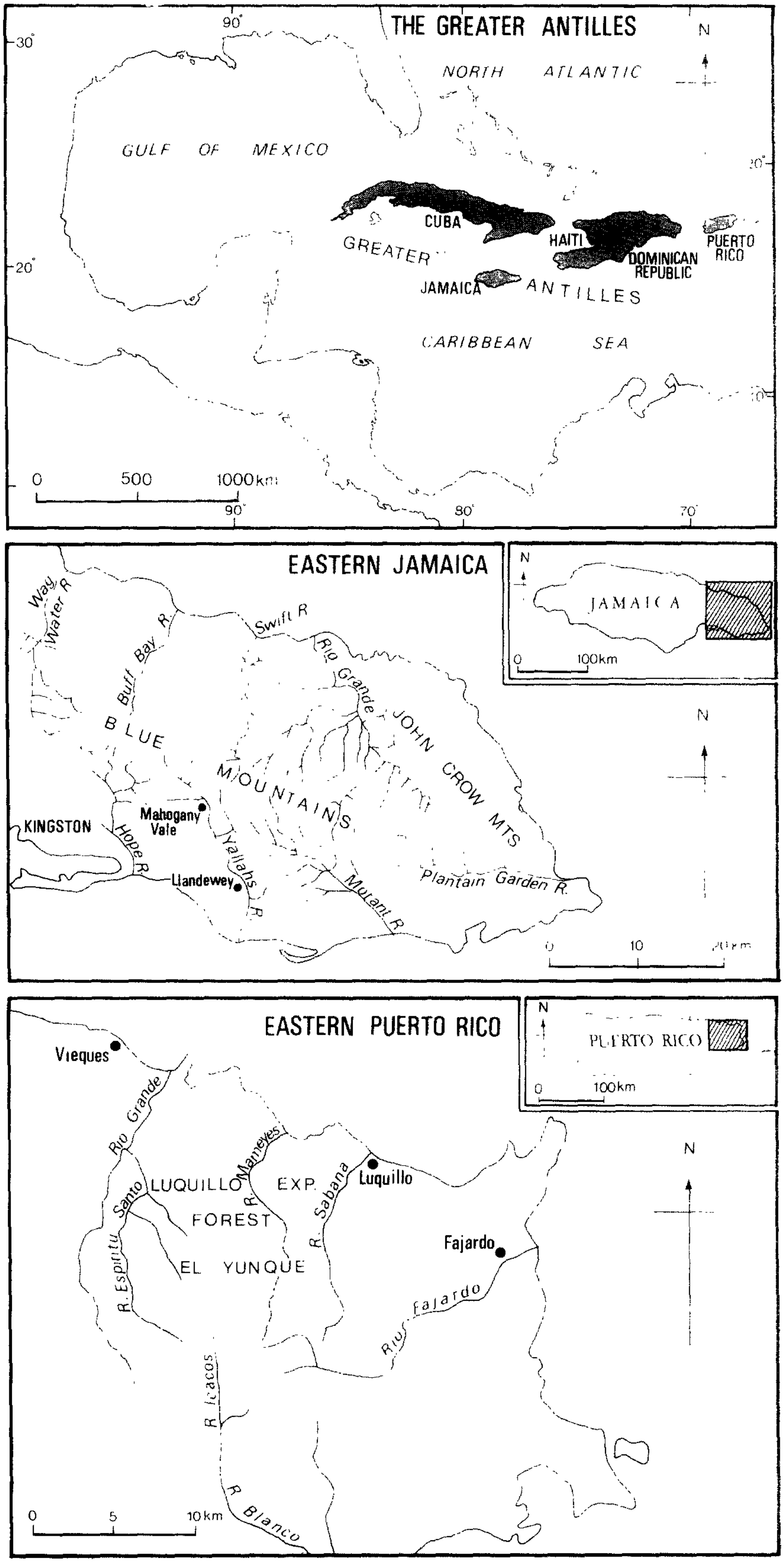

Fig. 1. Location map.

tains of eastern Puerto Rico (Fig. 1). Apart from data collected in the field, we use existing hydrological and sedimentological information on several of these streams. The published literature contains descriptions of two of the Jamaican rivers (Gupta, 1975); a headwater drainage system in Puerto Rico (Scatena, 1989); the effect of a recent hurricane on drainage in eastern Puerto Rico (Scatena and Larsen, 1991); and numerous studies of mass movements on these slopes. After setting up a regional model, we show several cases of small-scale deviation from the norm. Such deviations are based on local variations in lithology, neotectonism, hurricane frequency, landuse, and time elapsed since the inception of the valleys. The final stream channel reflects both the regional norm and any deviation superimposed on it.

The study area

Located within a 200 km wide seismically active zone of Neogene left-lateral strike-slip deformation that defines the plate boundary between the Caribbean and North American Plates (Fig. 2), this is an area of neotectonically controlled landforms (Mann et al., 1990). Landforms within strike-slip plate boundaries are currently attributed to oblique-slip extensional (transtension) or compressional (transpression) movements (Harland, 1971; Sanderson and Marchini, 1984; Mann et al., 1990). For example, transpression leads to uplift, manifested by mountains with steep dip-slip faults and a complex pattern of block faulting (Mann et al., 1985). The mountains of eastern Jamaica and Puerto Rico display landforms and drainage related to periodic tectonic movements.

The mountain areas at the eastern end of both islands are very similar. Running east–west, the mountain ranges rise abruptly from narrow fringing coastal plains. Several alluvial fans soften the break in slope between the mountains and plains. The Blue Mountains (Jamaica) are heavily faulted, and are mainly composed of volcanic rock, conglomerate, alternating sandstone and shale, and limestone of Cretaceous–Eocene age. The hillslopes are steep, often between 20° and 30°, and the relief between the ridge crests and the valley bottoms is from 450 to 600 m. The area receives from 760 to 6500 mm of rain each year, with a dry season between December and April on the southern slopes. Apart from patches of remnant forest, the slopes are covered by scattered trees, scrub or coffee bushes.

Most of the eastern mountains of Puerto Rico are under the Luquillo Experimental Forest (LEF). Cretaceous marine-deposited andesitic to

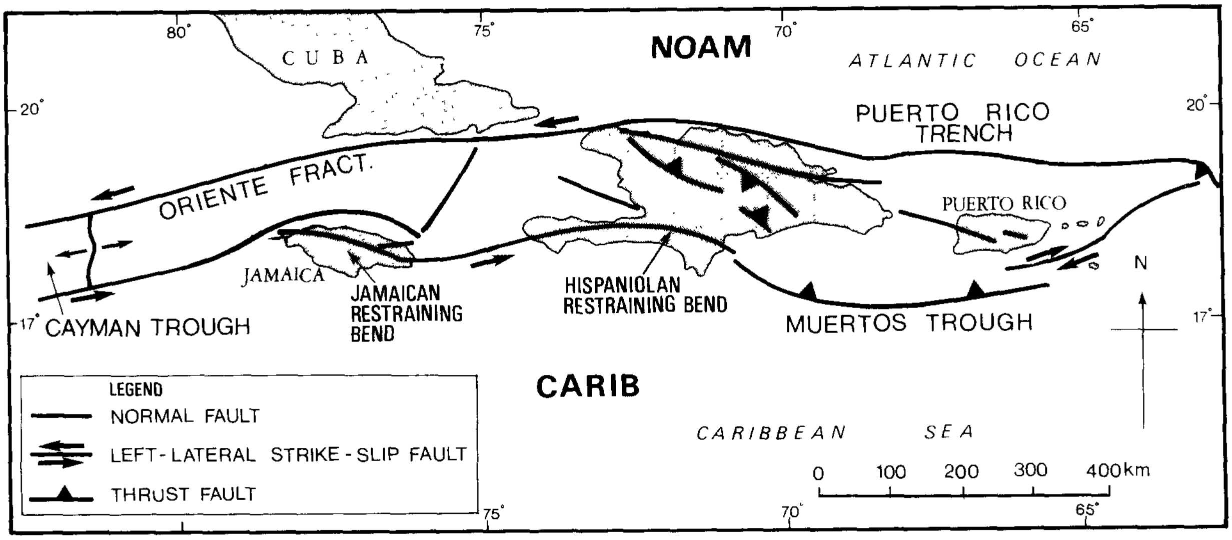

Fig. 2. Simplified tectonic map of the eastern and central sections of the boundary between the Caribbean (*CARIB*) and North American (*NOAM*) plates, after Mann et al., 1990 and Pindell and Barrett, 1990.

basaltic volcaniclastics (Seiders, 1971) are the dominant country rock with a Paleocene quartz-diorite intrusive body occurring towards the southeast. The central range with the highest peak at 1340 m is flanked by a 8–16 km wide coastal plain. The annual rainfall ranges from 760 to over 5000 mm depending on elevation and aspect (Brown et al., 1983). Although no month is dry, May, October, and November are particularly wet. As in the Blue Mountains of Jamaica, tropical storms and hurricanes occur periodically.

Tropical storms and hurricanes

Between 1886 and 1968, Jamaica and Puerto Rico experienced 45 and 35 tropical storms, respectively (Alaka, 1976, fig. 1). For Jamaica, using a Poisson distribution function, the probability of a hurricane affecting the island in any given year is 0.27. Counting direct hits only (16 since 1871) the probability is 0.14 (ODP and WMO, 1988). For Puerto Rico the return period is 21 years (Salivia, 1972) which gives a probability of 0.047 in any given year. Hurricane frequency, however, is not uniformly distributed. More hurricanes came to Jamaica in the two decades 1910–1919 and 1930–1939, nine for each period. Since 1960, the number has dropped off considerably (ODP and WMO, 1988). Hurricanes have occurred in clusters also in Puerto Rico (Scatena, 1989). Hurricanes affect large areas of the Luquillo Mountains once every 25–30 years, and pass directly over the forest once in 50–60 years (Scatena and Larsen, 1991).

TABLE 1

Selected flood discharges of rivers in Blue Mountains, Jamaica and Luquillo Mountains, Puerto Rico

River and location	A^d (km^2)	Peak Q (m^3/s)	Unit Q ($m^3 s^{-1} km^{-2}$)	Remarks
Jamaica				
Yallahs at	60.9	523.5	8.6	Gilbert (estimate)
Mahogany Vale		729.2	12.0	1973 peak
		707.0	11.6	100-yr R.I. (H.E.C. 1 estimate)
Yallahs	123.3	672.8	5.5	Gilbert (estimate)
at Llandewey		963.0	7.8	1979 peak
		1297.2	10.5	100-yr R.I. (H.E.C. 1 estimate)
Rio Grande	214.9	4249.3	19.8	Gilbert (estimate)
at Fellowship		4255.0	19.8	14 May 1982
Puerto Rico				
Espiritu Santo	22.3	566	25.4	recorded maximum
at Rio Grande		427	19.1	Hugo
Fajardo at Fajardo	38.6	666	17.3	Hugo
Icacos	3.3	81	24.5	recorded maximum
at Naguabo		70	21.2	Hugo
Mameyes at Sabana	17.8	580	32.6	Hugo
Quebrada Sonadora at El Verde	2.6	63.2	24.1	recorded maximum

Source: ODP and WMO (1988); Scatena and Larsen (1991), also compiled from various field sources.
Hugo, Gilbert = hurricane events.
H.E.C.1 = computed flood magnitude using H.E.C. 1 computer program.

Rainfall in any of these events varies widely. Hurricane Gilbert, described as the biggest hurricane of the century for Jamaica, produced a maximum of 794 mm of rain in the mountains giving rise to floods with only 25-year recurrence interval (ODP and WMO, 1988). On the other hand, Silver Hill in the Blue Mountains received 2451 mm in 4 days of November 1909 (Vickers, 1967). Lirios (1969) estimated that 24-hour precipitation between 250 and 635 mm can be expected in the Blue Mountains once in every ten years. The cumulative total for several storm days will be higher. Similarly, rainfall associated with the last six hurricanes to pass directly over Puerto Rico has ranged from 135 to 725 mm (Scatena and Larsen, 1991). At times, greater daily rainfall and flooding have been associated with non-hurricane tropical storms. The floods are tremendously destructive of existing gauges which makes the coverage and quality of flood information limited. We have been able, however, to produce Table 1 from the existing information, showing the repeating nature of high-magnitude floods on both islands.

Mass movements

In the mountains of Jamaica and Puerto Rico, mass wasting is probably the most important agent supplying detritus to stream channels. Both field observations and available stream sediment data indicate that bedload is unusually large in amount relative to fine-grained material (Gupta, 1975; Simon and Guzman-Rios, 1990; Simon et al., 1990). Numerous mass movements have been mapped for both the Blue (Gupta, 1975) and Luquillo (Guariguata and Larsen, 1990) Mountains. Short-duration, high-intensity rainfall events cause shallow soil slips and debris flows, whereas long-duration events, such as tropical storms, could be followed additionally by larger and deeper slides. Simon et al. (1990) have discussed the mechanism and causes of slope failures. In spite of local occurrence of 9 m of soil and regolith, the slopes are not everywhere covered by thick soils and a deep weathered mantle. This, presumably, is another indicator of the continuing erosion of these hillsides. Sediment moving downslope is commonly soil and weathered material, but in places large pieces of bedrock are added to it.

After a large rain-producing event, such as a tropical storm or a hurricane, the slopes are marked with innumerable shallow soil slips, debris flows along almost every first- and second-order channel (at times down even larger tributaries), and landslides with an average thickness of tens of metres and surface area that ranges up to tens of thousands of square metres (Howard Humphreys, 1967–68; Dames and Moore, 1980).

Landslides from the last two large hurricanes (Gilbert in Jamaica, 12 September 1988; and Hugo in Puerto Rico, 17–18 September 1989) have been carefully mapped. In Jamaica, Manning et al. (1992) mapped 478 landslides along 108 km of road section in the Lawrence Town-Above Rocks area northwest of Kingston. Debris flows were most abundant, but rock falls, translational slides, and complex rotational slides also occurred. Comparable incidents were seen though not mapped throughout the Blue Mountains. In large storms, mass movements are accelerated by the destruction of vegetation followed by near-horizontal intense rainfall on the slopes.

More than 400 landslides occurred in the LEF during or shortly after the passage of Hugo. The surface area of individual landslides varied between 18 and 4500 m^2 with a median size of 148 m^2. Less than 1.5 m deep soil slips and 1.5–2 m deep debris flows together made up 91% of all mass movements. This was the pattern for both forested and disturbed slopes. Even in the forests, landslides affected 0.11% of the area, indicating that storm-related mass movements are part of the regional geomorphic system. Up to fifteen mass movements per km^2 were counted after Hugo. The records indicate that shallow soil slips, debris flows, and slumps occurred during or immediately after the passage of Hurricane Hugo (Larsen and Torres Sanchez, 1992).

The largest mass movement was a debris avalanche which followed the track of a 1970 avalanche. Measuring 153 m in length, 27–332 m in width, and 3–10 m in depth, it moved 30,000 m^3 of soil and rock 600 m downslope into the river and exposed bedrock along the scar. This

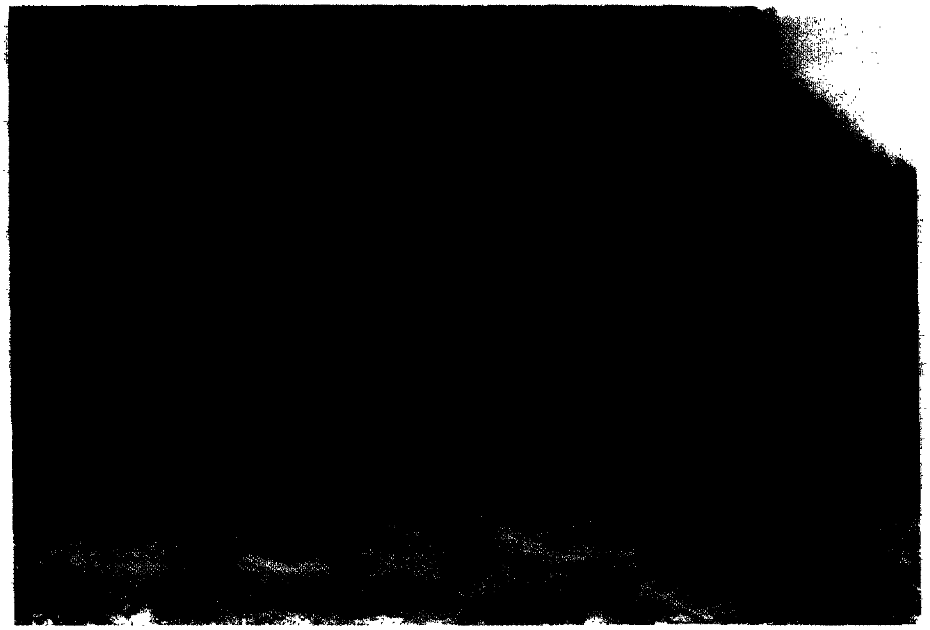

Fig. 3. Large landslide contributing sediment to the Yallahs River near Mavis Bank, Jamaica.

happened three days after the hurricane (Larsen and Torres Sanchez, 1992). Slides of such dimensions (Fig. 3) have been reported from the mountains of both islands after tropical storms and hurricanes (Gupta, 1975): the biggest reported in Puerto Rico was up to 100,000 m^3 in volume (Larsen and Torres Sanchez, 1992).

Apparently, the largest historic landslide in the Caribbean is the aptly named Judgement Cliff Landslide (Fig. 4) which followed the Great 1692 Port Royal Earthquake and heavy rainfall associated with a hurricane. This complex slide, which dammed up the Yallahs River, involved both slump and rockfall, and displaced over 80,000,000

Fig. 4. The Judgement Cliff Landslide, Jamaica.

m^3 of limestone blocks, boulders, and fine limestone debris mixed with clay and shale of the basement rocks (Zans, 1959). Large landslides after a tropical storm have repeatedly brought huge quantities of material down to river channels.

Larsen and Torres Sanchez (1992) have calculated the rates of material removed by landslides in the forests of Luquillo Mountains where 1.1% of the area is disturbed by landslides every 100 years. Hurricane Hugo eroded 11,767 m^3 of material from the area giving a denudation rate of 164 mm in 1000 years. In the field, almost the entire sediment is seen to come from 600 to 800 m elevation, a pattern of midslope destruction which is also evident for Jamaica. In time the upper slopes also become unstable.

Sediment liberated from the mountains is stored on the lower hillslopes or in the stream channels. The amount of sediment transported out of one of the closely monitored basins in Puerto Rico, the Mameyes, is approximately 300 t/km^2 annually. Larsen and Torres Sanchez (1992) have shown the total mass wasting contribution to be 81% of this. Mass movement is the prime supplier of sediment to the channels, and the material travels downvalley and out of the basin with brief periods of in-channel storage.

Fig 5. Landslide in volcaniclastics of LEF, clay-size material with embedded boulders.

The sediment supply is obviously pulsatory in nature, and the material shows a wide textural range heavily skewed towards the coarser fraction. In Jamaica, the material that comes down in shallow slides ranges between clay and fine pebbles; the debris flows are predominantly composed of pebbles but contain boulder-size material; and large (10^4 m^3) slides carry everything including large blocks of bedrock. In Puerto Rico, the shallow slides off the volcaniclastic rocks are essentially in clay with a few embedded boulder-size corestones (Fig. 5); the debris flows down tributaries carry coarse material, mainly boulders of 1–2 m; and the very large slides include the whole range. All this falls into the stream channels at various points along the course. In Jamaica, huge debris flows have blocked channels and built temporary lakes behind a wall of boulders.

The rivers

Water

The daily discharge tables for the rivers of the Blue and Luquillo Mountains show scattered episodes of several consecutive days of high flow. This is common between July and November although the annual peak discharge has arrived in other months in certain years. The flood flows are much higher than average discharges, and the flood hydrographs rise very steeply, at times almost vertically. The high flow, however, continues for more than one or two days only for very large storms. Notwithstanding the limited number of stream gauges in the Blue Mountains, the records show that the rivers of eastern Jamaica and Puerto Rico episodically carry large volumes of floodwater at high velocity (Table 1).

Sediment

A very large proportion of the sediment in these rivers (Fig. 6) can move only as bedload, and boulders ranging up to several metres need very high velocity for transportation. Estimated peak velocities for Jamaican rivers during Hurricane Gilbert ranged from 1.2 to 7 m/s (ODP and WMO, 1988). The Yallahs River at the apex of its fan delta had a peak velocity of 3.9 m/s, sufficient to move some of the boulders. After this flood, deposition of coarse material up to boulder size blocked the crossing on the Yallahs about 3 km downstream of the apex. The deposited material spread out over the fan beyond the banks, and accumulated as high as the roof of one-story shops about 200 m from the river (ODP and WMO, 1988). Similar deposition occurred at the same place in 1963 after the passage of Hurricane Flora. Bank erosion after the passage of each of these floods adds to the considerable amount of coarse material already resting within the channel and the new material coming down via different types of mass movements. The coarse sediment then moves in pulses down the rivers, and between the movements builds boulder berms, channel bars, and hurricane terraces at suitable places, as described elsewhere (Gupta, 1988).

Morphology

The valleys of the eastern mountains of both Jamaica and Puerto Rico tend to be straight with a few near right-angled bends. The tributary junctions are frequently perpendicular to the main stream, and the drainage nets on topographical maps show a number of straight low-order tributaries. The channels occupy a disproportionately large width of the valley floor, and at times steep hillsides rise from the banks themselves.

Such attributes strongly suggest that the valleys are structure-guided. Evidence of faulting has been seen along some of the tributary valleys, and the courses of larger ones, such as those of the Yallahs or Wag Water River, tend to coincide with fault zones on geological maps. This gives rise to steep-sided, easily erodible valleys where side slopes are heavily denuded by mass movements which tend to open up the valleys and contribute large volumes of coarse sediment to the channels. These streams are confined in their courses and cannot aggrade except in their lower courses near the coastal plains or where the valley is locally wider over a short distance.

The long profiles of the streams are also steep. The gradients range from 0.061 to 0.241 when calculated from topographic maps. Locally, how-

Fig. 6. Storage of sediment in the Sabana River, Puerto Rico.

Fig. 7. Boulder accumulation, Swift River at Chelsea, Jamaica.

ever, the streams flow through narrow steeper reaches in gorges and at places plunge over waterfalls and rapids where bedrock is exposed.

Along their courses these streams descend another type of rapids in a series of small steps, 0.5 to 1 m in height. Such rapids are built by accumulation of boulders over bedrock. The origin of such boulder accumulations, stretching over hundreds of metres (Fig. 7), needs an explanation. Part of it could come from exhumed corestones, but there are reported cases from Jamaica (Chelsea on the Swift River and Milbanks on the Rio Grande), where large debris flows in the past have blocked the channel creating a temporary

Fig. 8. Boulders scattered across Swift River channel, downstream from Fig. 7.

lake upstream. In both these places the rivers, as described above, flow in a series of rapids in a more than 100 m long reach full of large boulders from bank to bank. Such boulders, typically 1–2 m in median diameter but locally larger, are exotic in the sense that they do not match the valley bedrock. At both Chelsea and Milbanks, the path of a debris flow from a huge scar up on the hillside to the channel may still be identified and remains well known to the local inhabitants. The boulder zone stretches across the entire channel and no deposition of bars is seen in these places. Similar features have been described for the Colorado River in the Grand Canyon (Graf, 1979; Webb et al., 1989). Moving downstream, boulders become more scattered (Fig. 8), rising out of the water level. Further downstream small bars in pebbles and cobbles with several large boulders perched on top start to appear. The bars gradually become bigger and the perched boulders die out.

We suggest that the coarse material in the channels originates from a combination of valley-side slides, debris flows along tributaries, and from storage in valley alluvium in wider sections. Large inputs of very coarse material come in either as huge debris flows or as large landslides measured in 10^4 m^3. The entire material is then eroded and redistributed to form various types of bars (Gupta, 1975), depending on the local conditions.

These mountain streams for most of their courses flow over a shallow layer of sediment above bedrock. At places where the valley is narrow, bedrock is exposed both on the banks and the floor. The streams therefore are bounded in rocky channels and behave as conduits for transporting a shallow layer of coarse material beyond the mountains to the coastal plains.

Where locally the valley widens, it becomes an area of deposition. The form of deposition, moving from midchannel to the valley walls, includes channel bars, floodplains, and flood terraces (Gupta, 1988). Such features survive until the next high-magnitude flood which erodes them, and subsequently transports sediment downchannel. With the falling stage of the hydrograph the sequence of events begins again.

A suggested model and its variations

The above is a description of the morphology and behaviour of the montane streams of Jamaica and Puerto Rico. One of us has earlier attributed

Fig. 9. Boulders in Quebrada Sonadora draining volcaniclastic rocks of the Luquillo Mountains, Puerto Rico.

the Blue Mountain valley-floor forms and sediment to high-magnitude floods (Gupta, 1975, 1988). It is now suggested that the type and amount of sediment supplied to the streams and the nature of the drainage system are dependent, in addition, to the location of these streams within a strike-slip plate boundary zone. A comparison of two islands which share this tectonic environment and also a storm-prone climatic regime helps us to build a conceptual model of the montane Caribbean rivers.

Rivers of the Greater Antilles may be ex-

Fig. 10. (A) Meandering Rio Icacos with sandy point bars in Luquillo Mountains, Puerto Rico. (B) Channel modification by a quartz–diorite boulder. The boulder is in the middle of a cross-over creating scour pools around it. In other places, boulders have forced the stream into very sharp turns creating a meander bend with a boulder as the meander cliff.

pected to have the following properties. (1) The drainage density is low with the tributaries joining the main stream at high angles. (2) In the mountains the valleys are narrow and deep with landslide-affected steep sideslopes and confined stream channels. (3) Stream gradient is high, with local rapids at rock outcrops or boulder accumulations. (4) Valley alluvium is characterised by extremely coarse sediment. (5) Braiding, multiple channels, and bars are found where the valley widens, either locally or near the coastal plains. In meandering streams an enlargement of point bars in coarse sediment is common at such places. (6) The depositional forms built by sand, pebbles, cobbles, and boulders are related to both the passage of high-magnitude floods (Gupta, 1975, 1988) and size and age of the nearest large landslide.

These are features which are common in the montane streams of eastern Jamaica and Puerto Rico. Superimposed on this are variations that occur at smaller scales. An earlier study has shown that seasonality in discharge causes the rivers to braid, and meandering streams with point bars in coarse material occur where pronounced seasonality is absent (Gupta, 1975). In the Luquillo Mountains, streams draining volcaniclastics carry boulder-size material (Fig. 9). There is hardly any sand, and the little clay or silt that comes from the weathering of rocks is carried out of the mountains as suspended load in floods. The streams are very clear even a few hours after the passage of the peak flow. The streams typically display boulder accumulations or exposed bedrocks separated by stretches without any deposition but not deep enough to be identified as pools. In contrast, the rivers draining the quartz–diorite body carry large volumes of sand, and build point bars. The big boulders, however, are channel modifiers (Fig. 10), and right-angled bends are found where the streams encounter these boulders. At cross-overs where meander geometry dictates a shallow passage, the presence of a boulder ensures a deep pool scoured round its base. The current anthropogenic destruction of vegetation on Jamaican slopes has led to sediment contribution at a much faster rate. It will be fascinating to monitor the rivers to see how they adjust to this increase in sediment load. Overall, these streams are the product of tectonic activities, mass-movement-derived coarse sediment in profusion, and high-magnitude floods at intervals.

We believe that the riverine forms and valley alluvium in a plate boundary strike-slip zone are diagnostic, especially if high-magnitude floods are also common. Examinations of past sediments, such as the suspected Quaternary high-terrace material in the Yallahs Valley (Gupta, 1983), or the Eocene sedimentary rocks of the Blue Mountains (Robinson et al., 1970; Wescott and Ethridge, 1980), can be interpreted as flood derived. We need further work in these valleys to find out if the petrology of the coarse paleoalluvium or sedimentary rocks, and the texture and structure of the sediment, reveal furthermore the presence of a former tectonic zone.

Conclusions

The channels in the eastern mountains of Jamaica and Puerto Rico are controlled by neotectonic movements, periodic high-magnitude floods, and a plentiful supply of coarse bedload. This is due to the location of the islands within a Neogene left-lateral strike-slip plate boundary zone, which is also an area periodically visited by tropical storms. The morphology of the channels is characterised by steep slopes, near-vertical banks, low sinuosity, and an accumulation of boulders. The wider reaches show floodplains and flood terraces at various levels. Superimposed on this general pattern, variations occur at smaller scales due to the presence of seasonality in rainfall or a particular lithology exposed as bedrock. Standard descriptions of channel form and behaviour do not work adequately for these rivers.

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