

## STREAM CHARACTERISTICS IN EASTERN JAMAICA, AN ENVIRONMENT OF SEASONAL FLOW AND LARGE FLOODS

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**ABSTRACT.** This paper describes channel form and stream behavior in a type environment, that of seasonal tropics with periodic high-magnitude rainfall. The area chosen for study is the Blue Mountains, the central massif of Eastern Jamaica. Both slopes of the Blue Mountains display similar geology, relief, high annual rainfall, soils and land use, but the southern side has a wet and dry seasonal regime, whereas the northern slopes experience a uniform distribution. Comparison of a north-slope stream (the Buff Bay) with a south-slope stream (the Yallahs) shows distinct differences in channel form and stream behavior. The Yallahs has a wide, shallow, flat-bottomed, braided channel with steep banks, whereas the Buff Bay meanders in a deep, round-bottomed channel with sloping banks. Tributaries graded to the main stream join the Buff Bay, but unaccordant tributary junctions are found in the Yallahs. Similar differences are seen on a regional scale when one compares the north-flowing streams with the south-flowing ones in Eastern Jamaica. The varying ability of the south-flowing rivers to erode and transport at different seasons is probably responsible for their wide, shallow, braided appearance, so common for streams in regions of seasonal precipitation.

The river valleys in the mountains of Eastern Jamaica are also affected by large floods that occur on the average every 10 yrs. Since floods of such magnitude happen rarely, their effects on the landscape are temporary, being modified by normal geomorphic processes. However, the landscape in the valleys of Eastern Jamaica includes permanent forms created by large floods along with forms created by common events like bankfull discharge. The flood-originated forms include low terrace-like features in the valleys, coarse channel and floodplain sediments, and modification of vegetation in the higher parts of the valley bottom.

### INTRODUCTION

Examples of seasonality in precipitation are found in different parts of the world. South and Southeast Asia, West Africa, and the Mediterranean region would provide good samples. This paper examines the hypothesis that seasonality significantly affects channel form and behavior by analytically comparing two streams having equivalent milieu in all respects except flow regime. If the rivers exhibit different stream processes and channel morphology, then from such a "controlled experiment" one may conclude that the seasonality in rainfall is responsible since other environmental influences are the same.

The field area chosen for this investigation is in the eastern part of the island of Jamaica in the Caribbean Sea (fig. 1). Generally east-west trending chain of the Blue Mountains runs through the middle and is ringed by narrow coastal plains which extend inland along major river valleys such as the Wag Water, Buff Bay, Swift, and Rio Grande on the north coast and the Hope, Yallahs, Morant, and Plantain Garden River on the south. The northern and southern slopes of the Blue Mountains have a comparable physical environment, but rainfall is uniform on the north slopes while the south slope experiences a dry and wet pattern. A

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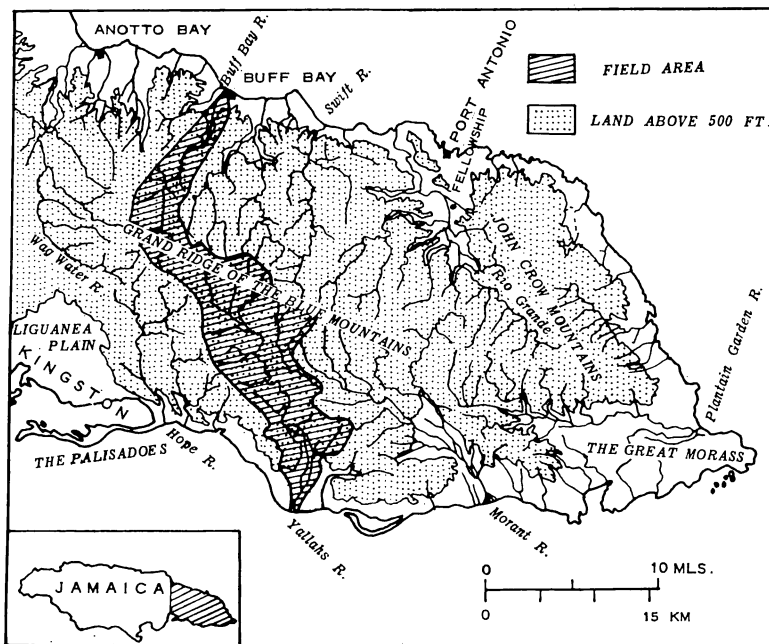


Fig. 1. Eastern Jamaica: location of the Yallahs and Buff Bay River Basins.

representative river from each side of the mountains was chosen for detailed investigation, the Buff Bay River on the north and Yallahs River on the south, the two drainage basins being separated by a divide averaging over 1250 m in altitude.

These valleys are also exposed to frequent, high intensity rainfall, and "catastrophic" floods about once in a decade giving rise to characteristic flood-originated valley forms and sediments. Such forms and sediments are described in this paper to complete the story of streams adjusting in humid tropics with periodic high flooding.

#### PHYSICAL GEOGRAPHY OF THE FIELD AREA

*Geology.*—The Yallahs and the Buff Bay River Basins are underlain primarily by rocks of Cretaceous and Tertiary age, skirted on three sides by an almost continuous narrow band of Tertiary and Quaternary formations. The geology of the Yallahs and Buff Bay River Basins is comparable. The different geological formations exposed in the Yallahs and the Buff Bay River Basins are shown in a general way in figure 2. Details of the geology of Eastern Jamaica are in Zans and others (1962), Cant (ms), Kemp (ms), and Robinson, Lewis, and Cant (1972). Graywackes and shales of Richmond Formation and conglomerates, sandstones, and mudstones of the Wagwater Formation underlie most of the basins along with Newcastle Volcanics and younger limestones. The alluvium in the middle and lower courses of the two rivers is also similar. A valley-fill

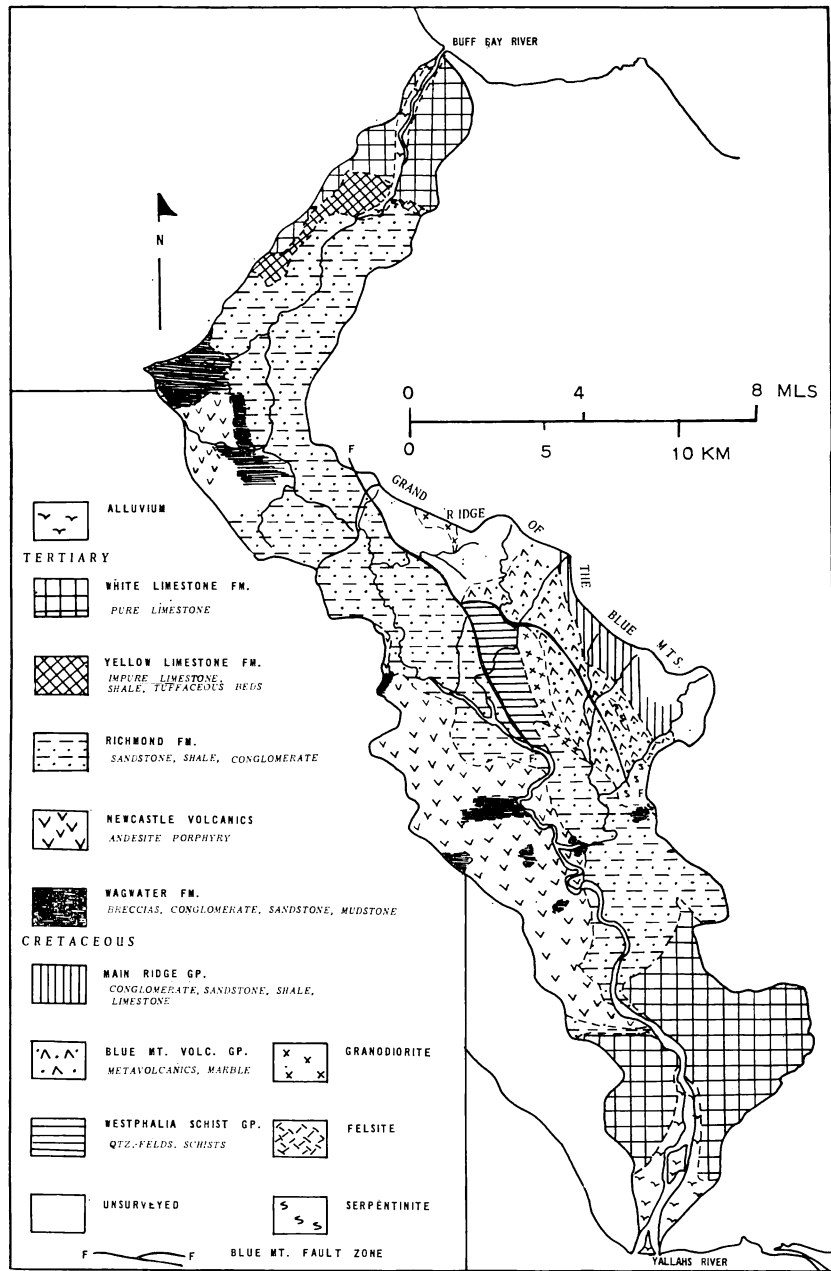


Fig. 2. Generalized geological map of the Yallahs and Buff Bay River Basins.

of older alluvium is present below the bed material of the rivers of Eastern Jamaica. (Andrew, 1969; Harza and Chin, 1971).

*Physical features.*—Both basins are predominantly hilly with steeply demarcated narrow riverine plains that bulge out in fans at the mouths of the Yallahs and Buff Bay. The Grand Ridge of the Blue Mountains with peaks above 1400 m and culminating in the 2256 m high Middle Peak forms the divide between the Buff Bay and the Yallahs Basins. In general the mountain ridges in Eastern Jamaica follow the Grand Ridge and trend roughly northwest-southeast. The common feature of these two river basins is the impressive and persistent local relief of 450 to 600 m with steep slopes at angles between 20 and 30 degrees. Plains are found only along large rivers, such as the Yallahs, Green, or Buff Bay. Stream frequency figures for the Buff Bay and Yallahs are respectively 10.9 and 12.6 per square km showing comparable degree of dissection. Weathering of bedrock is extensive, but shallow presumably because of steep slopes, frequent mass movements, and high velocity slope-wash following intense rainfall.

Figure 3 shows the location of important landslides in the Yallahs and Buff Bay Valleys plotted from aerial photographs and field investigation indicating the importance of landslides as a geomorphic process in the two river basins. The occurrence of these landslides may be explained by the lithological, stratigraphic, and structural weakness of rocks of the Blue Mountains which gave rise to slides under periodic torrential rainfall. For example, in October 1963, as a result of precipitation from hurricane Flora, the Yallahs undercut part of the left bank downstream of the Mahogany Vale Footbridge, initiating a landslide of approximately 40,000 cubic m from shattered and fractured Richmond Beds (Howard Humphreys, 1967). Destruction of natural vegetation has also accentuated the problem.

*Rainfall.*—Figure 4 illustrates the distribution of mean annual rainfall. About 90 percent of the Buff Bay Basin receives an annual rainfall of more than 250 cm, and the amount ranges from 230 to 380 cm. The Yallahs Basin receives between about 150 and 320 cm. The rainy season from September to the middle of December is followed by clearing of skies and a drier spell till April, especially pronounced south of the Blue Mountains. Rains begin in May, though they are not as heavy as in September through December. For the purpose of this paper, the rainfall in Eastern Jamaica has been divided arbitrarily into two periods — rainfall from December through April and rainfall from May through November. The first period is designated the Dry and the second the Wet Season. The total rainfall in the December-April period was determined as a percentage of the mean annual total for each station and isopleths drawn to show the distribution of rainfall in this period over the Buff Bay and Yallahs Basins (fig. 5). The isopleth distribution indicates that the percentage of rainfall during the dry season gradually decreases from north to south. Assuming an evenly distributed rainfall

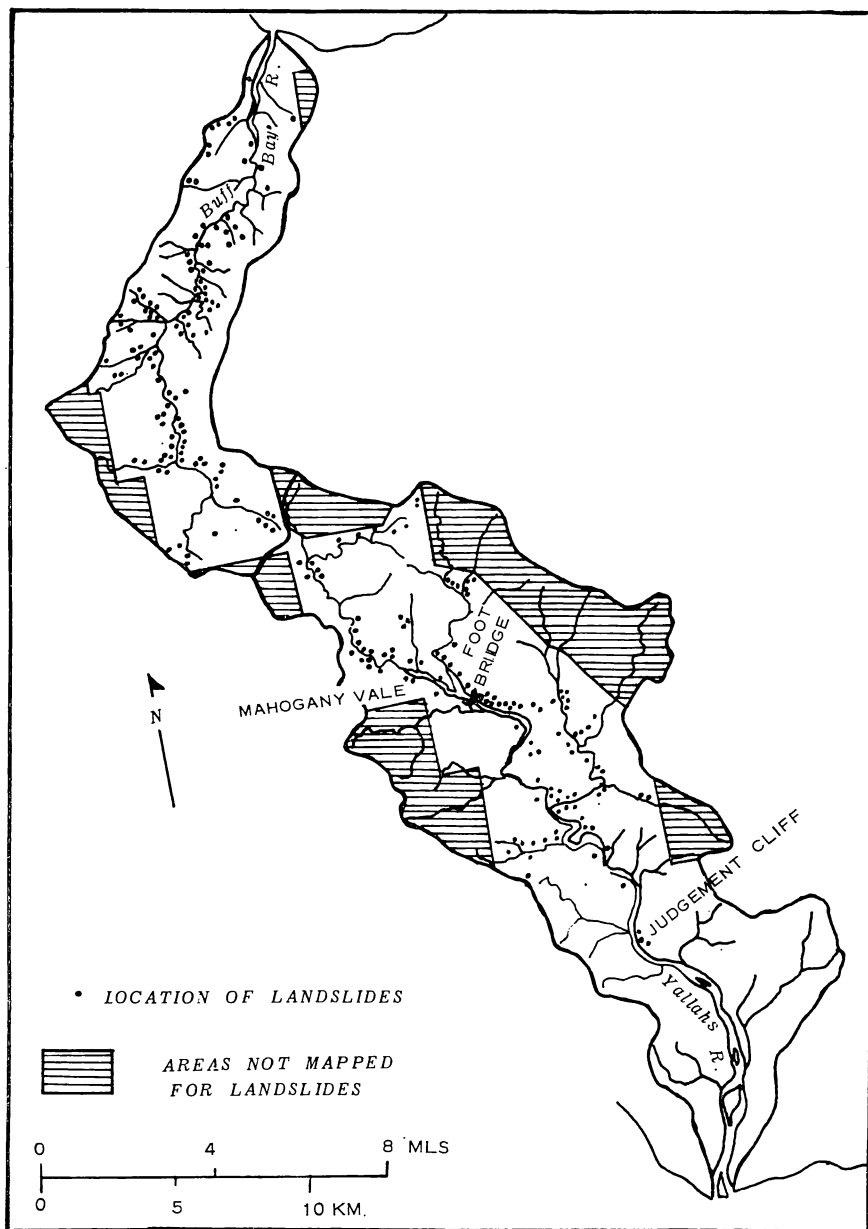


Fig. 3. Landslides in the Yallahs and Buff Bay Basins.

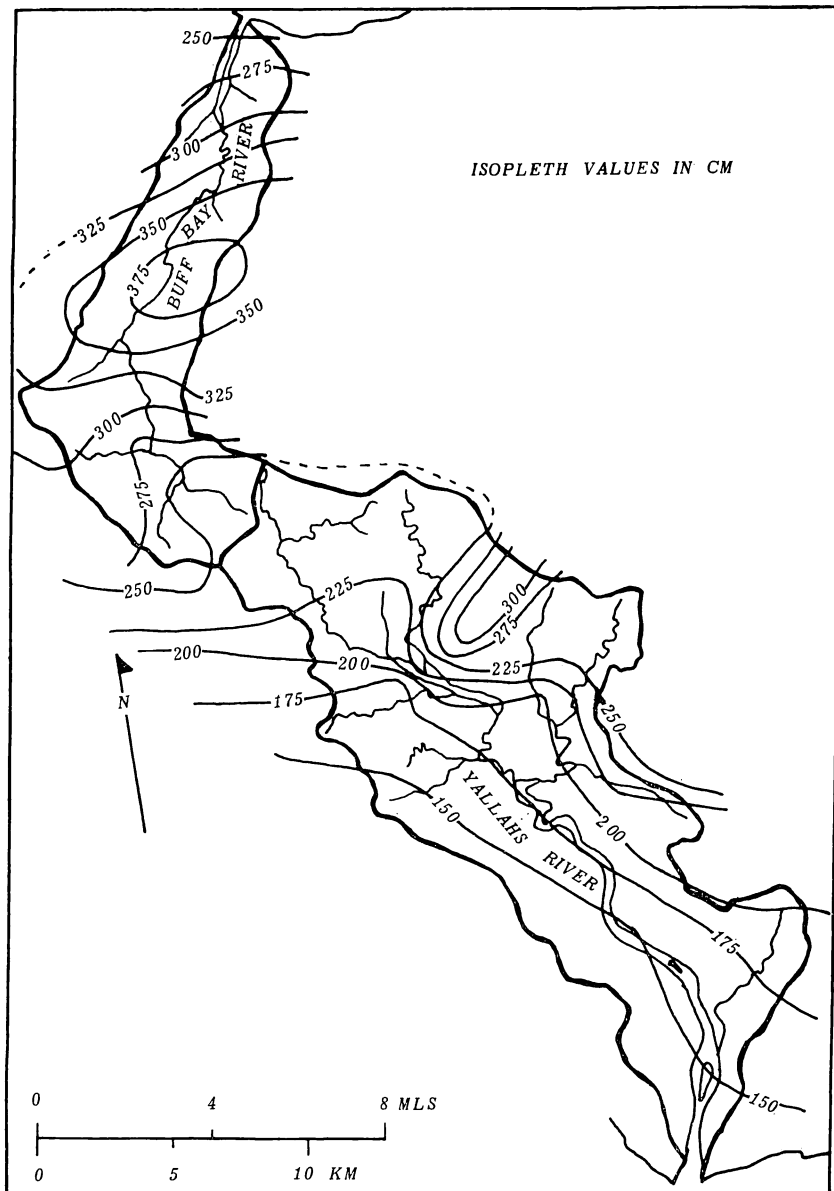


Fig. 4. Distribution of mean annual rainfall: Yallahs and Buff Bay Basins.

of a little more than 8 percent each month, about 40 percent of the annual total would fall between December and April. The northern 60 percent of the Buff Bay Basin receives between 40 and 45 percent. Farther to the south the rainfall percentages drop and ultimately extend below 25 percent in the extreme upper headwaters, on the Buff Bay-Yallahs Divide. The Yallahs Basin on the other hand never receives much above 25 percent of its annual rainfall during these 5 dry months. In fact the southern 60 percent of the basin receives less than 20 percent, the lowest being about 13 percent near the Yallahs mouth. During the wet season with an evenly distributed rainfall of roughly 8 percent per month, slightly less than 60 percent of the rainfall should occur between May and November. Most of the Buff Bay Basin receives between 55 and 60 percent, indicating a quite uniform rainfall regime. In contrast, the southern 85 percent of the Yallahs Basin receives more than 70 percent of the annual rainfall during the wet 7 months. The southern half receives over 80 percent, and over the Yallahs Fan the percentage reaches 85 percent.<sup>1</sup>

Intense rainfall of impressive magnitude occurs intermittently in Jamaica from cold fronts moving southward from the temperate areas, waves in the easterly, and tropical storms occasionally reaching hurricane force. Rainfalls of nearly 250 mm a day or 1000 mm in 3 days are not rare on the island (Vickers, 1967). Apparently precipitation of 250 to 635 mm in 24 hrs can be expected in the Blue Mountains once in every 10 years (Lirios, 1969). The maximum rainfall recorded in the field area is 2451 mm at Silver Hill during 4 days of November 1909. Translated in terms of river flow, this implies catastrophic flooding on a periodic basis.

*Vegetation and land use.*—Very little remains of Jamaica's original vegetation following exploitation of virgin woodlands by man especially in the last 400 yrs. Plantation agriculture resulting in the cultivation of sugarcane, coffee, tobacco, cotton, and cinchona replaced the vegetation on the plains and up to about 1370 m in the hills. The upper parts of both Yallahs and Buff Bay basins are among the very few places where the native Jamaican vegetation has survived. Elfin woodlands high up on the Grand Ridge are progressively succeeded downslope by montane mist forest, lower montane forest with shrubs and grasslands in the valleys, dry limestone forest, and grasslands with open thorn woods in the lower alluvial plains down to the sea. However, over large areas the spread of cultivation has destroyed the original vegetation, and though there may be relicts in the less accessible places, in general one finds secondary growth (ruinate), burnt land, and cultivated patches. The upper slopes of both basins are under forest, and the lower slopes are under secondary growth or being cultivated (Adams, 1971, 1972; Paget, 1956).

<sup>1</sup> Flow-duration studies of the two streams were not used due to the existence of only one relatively long-term gaging record at Tranquility on the Buff Bay.

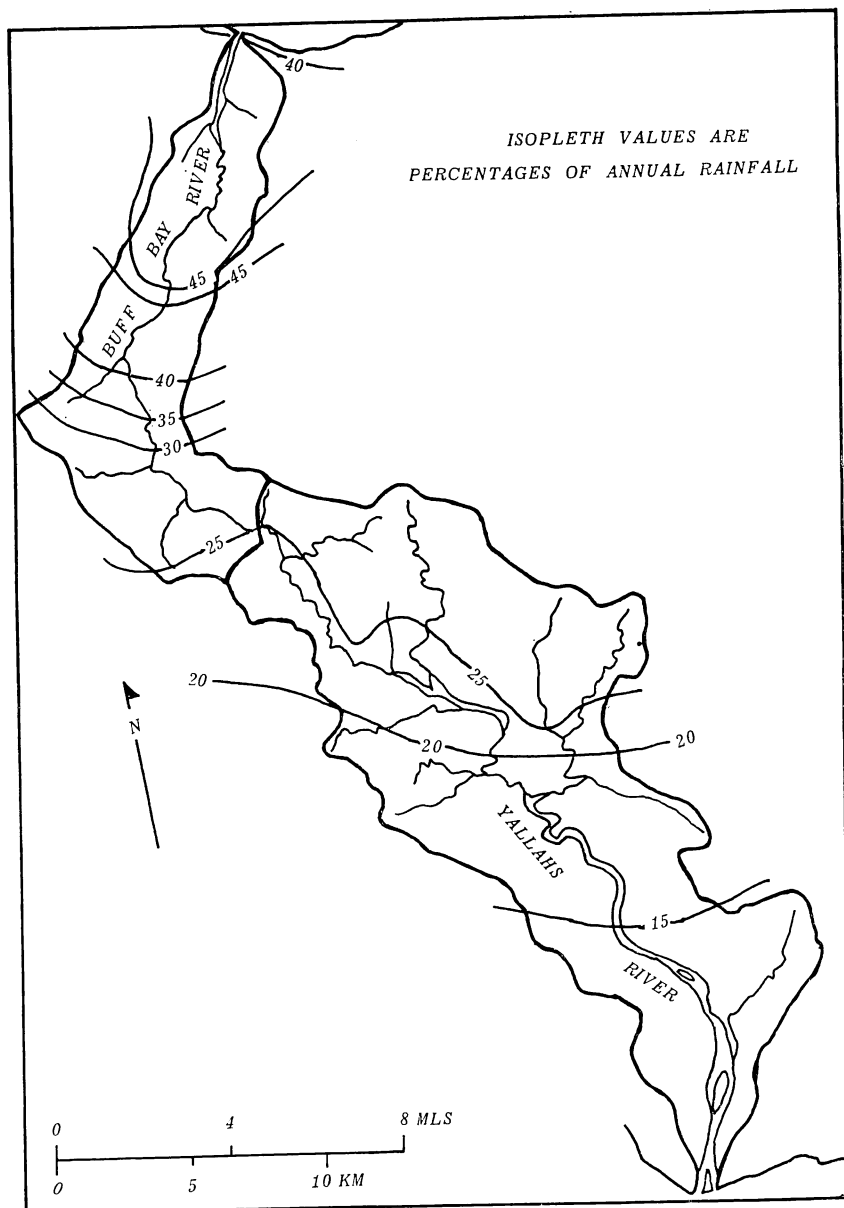


Fig. 5. Distribution of seasonal rainfall, December-April: Yallahs and Buff Bay Basins.

THE BUFF BAY RIVER

The Buff Bay River, a fourth order stream, rises at an elevation of about 1000 m on the northwestern slope of the Grand Ridge of the Blue Mountains and meanders northeast for 22.9 km to the Caribbean Sea. The valley of the river is characterized by several physiographic forms. A discontinuous terrace between 1.75 and 3 m above the floodplain of the river occurs locally at the base of the break in slope separating the plain from the hills. Less frequently there is a distinctive higher terrace approximately 9 m above the river. The floodplain and channel of the Buff Bay lie below the terraces. However, all features are not present at every section in the valley. The river has occasional straight reaches within a more common meandering pattern with point bars which with midchannel islands are the conspicuous depositional forms in the channel. Size of the bed material was determined by pebble counts (Wolman, 1954) and indicates a main maximum in pebbles or cobbles and a second one extensively in sand, deposition of fines being rare and local, chiefly on top of bars in overflow channel or in the lee of boulders.

TABLE 1  
Comparison of the environments of the Yallahs and Buff Bay Rivers

Factors	Yallahs	Buff Bay
1. Geology		
A. Type of rock forming the bed or underlying thin valley-fill for at least 5% of the total length of the channel	Richmond Turbidites—50% Alluvium and old gravels —29% Newcastle Volcanics —15% Limestone — 5%	Richmond Turbidites—60% Alluvium and old gravels —26% Limestone —14%
	99%	100%
B. Structural features	No appreciable difference	
2. Topography		
A. Landforms	Mostly hills. Narrow valley bounded by steep hillsides.	Identical
B. Stream Order	5	4
C. Channel gradient	Between 0.009 and 0.241	Between 0.011 and 0.161
D. Landslides	Extensive and periodic. Principal mode for supplying coarse detritus to the channel.	Same
3. Climate		
A. Annual rainfall	150 to 320 cm	230 to 380 cm
B. Mode of rainfall	Seasonal	No dry season
C. Intense high-magnitude rainfall	Intermittent	Intermittent
4. Vegetation distribution	Forests in the headwaters. Cleared patches and <i>ruinate</i> woodlands and scrubs lower down.	Comparable
5. Land use history	Similar in both	

The same coarse materials make up the banks except for the top 30 cm which are primarily sand and silt at places.

Stations were set up on the river in order to describe in detail the size, shape, and discharge of the channel (fig. 6). Traverses were run with a dumpy level at these stations located a few kilometers apart along the channel. Sections were measured from very low flows to almost bank-full conditions. To describe channel form for comparative purposes, it was decided to plot at-a-station hydraulic geometry curves for 5 stations (Leopold and Maddock, 1953). Rates of change of width, depth, and velocity with discharge have been tabulated (table 2) and indicate the following.

The rate of increase in depth ( $f$ ) in the Buff Bay River with increase in discharge is much greater than the corresponding rate of increase in width ( $b$ ). With rising discharge the Buff Bay gets noticeably deeper describing a boxlike channel. There is apparently an indirect relationship between the exponents  $m$  and  $f$ , as shown graphically in figure 7. With an increase in value of  $m$  there seems to be a corresponding decrease in the value of  $f$ . There does not seem to be any relationship between  $b$  and  $m$ . These combinations indicate that the principal adjustments in channel form in relation to discharge are in depth and velocity and not in width at these stations.

#### THE YALLAHS RIVER

Rising at an elevation of about 1500 m on the southern face of the Grand Ridge, the 37 km long fifth order Yallahs River drains about 163 square km of southern slopes of the Blue Mountains and parts of the south coastal plains of Jamaica. The sharp demarcation between the hillsides and the four physiographic forms in the valley, two terraces, floodplain, and channel, as described for the Buff Bay, also occurs in the Yallahs Valley.

Through the first 9.5 km of its course the Yallahs meanders through the mountains changing into a braided river with generally well-defined banks further downstream. The braided Yallahs usually has multiple channels with mid-channel bars separating them. Unlike the Buff Bay, the junction of the tributaries with the Yallahs is not always accordant, and broadly three types of tributary junctions occur in the Yallahs.

TABLE 2  
The Buff Bay River  
At-a-station change of width, mean depth, and velocity with discharge

Station	Drainage area km <sup>2</sup>	Number of observations	Value of exponents			
			b	f	m	b+f+m
Spring Hill	18.98	6	0.01	0.69	0.38	1.08
Balcarres	43.74	6	0.07	0.47	0.51	1.05
Tranquility	51.80	6	0.22	0.55	0.27	1.04
Charles Town	61.05	5	0.12	0.39	0.44	0.95
Buff Bay Town	63.17	6	0.12	0.67	0.25	1.04

Source: Field measurements.

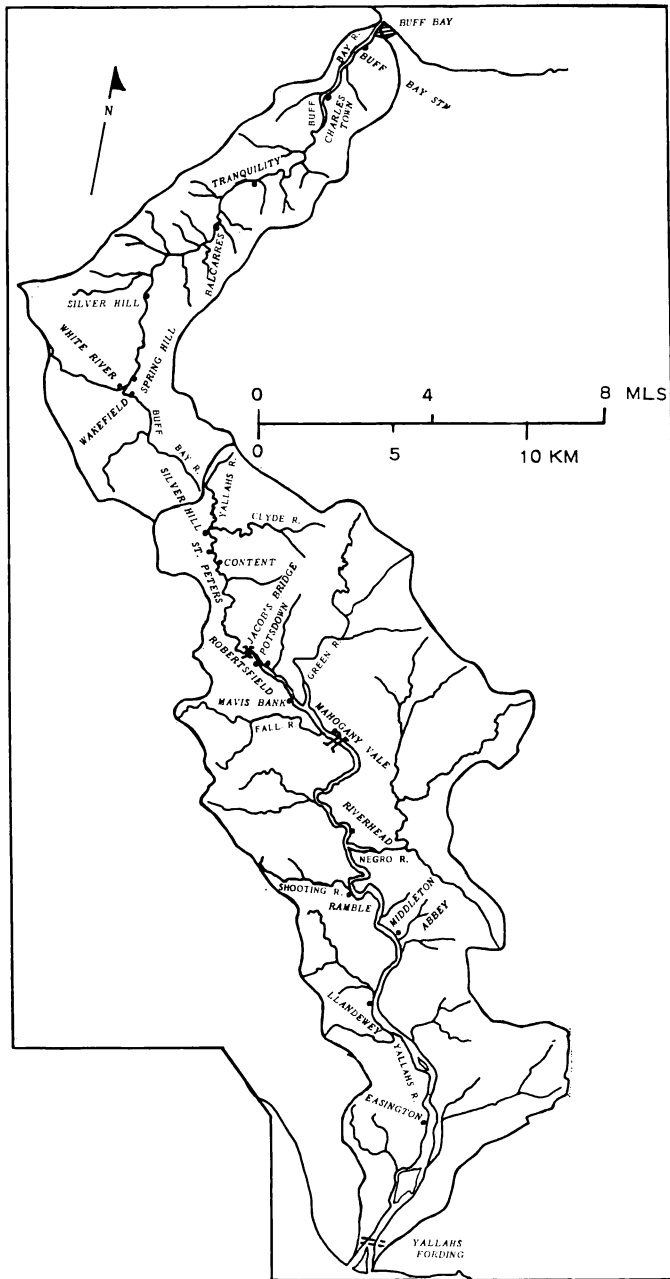


Fig. 6. Buff Bay and Yallahs Basins: location of field stations.

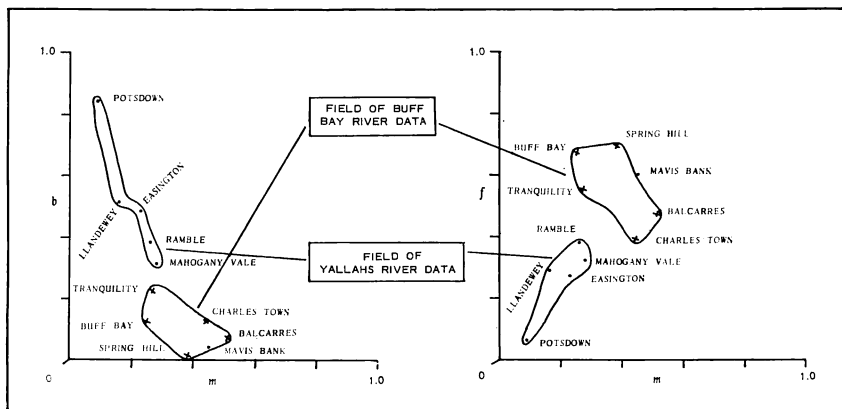


Fig. 7. Buff Bay and Yallahs Rivers: change in channel form with varying discharge.

*Hanging junction between the Yallahs and a very small tributary.*—There is normally a drop in the level of a first or second order tributary where it joins the Yallahs. Usually the tributary is graded to the floodplain of the river and not the channel. For example, the Shooting River, a second order stream, joins the fifth order Yallahs with the bed of the tributary being graded to the floodplain of the Yallahs, and water from the Shooting River trickling over the floodplain flows down the steep bank to the channel of the Yallahs.

*Normal junction between the Yallahs and a large tributary.*—The confluence with the Fall River is a good example of a tributary graded to the thalweg of the Yallahs River, one that does not “hang” like those of the previous class. These streams carry enough water at all times to maintain the channel across the floodplain of the Yallahs River.

*Junction between the Yallahs and a tributary comparable in size.*—There are only three confluences, Yallahs-Clyde, Yallahs-Green, and Yallahs-Negro, in which the discharge of each river is comparable, and except for the Negro, the streams at each junction have about the same drainage area. Invariably both streams at the confluence flow over rapids before joining and seem to deposit a very coarse part of the load they carry in flood immediately upstream of the confluence. The explanation is not obvious, but it could be due to alternate backwater effects on both rivers if comparable floods in each, at least their peaks, arrive at different times.

There is no difference between the bed and bank materials of the Yallahs River. The banks are not distinguished by accumulation of fines or distinct stratification. At best a weak fining-upward sequence may be discerned. Bed and bank materials of the Yallahs River were sampled at 6 stations — Silver Hill, Potsdown, Mavis Bank, Mahogany Vale Footbridge, Llandewey, and Easington — by pebble counts (Wolman, 1954). The material in the channel is very coarse, with a bimodal size distribution of bed and bank material at half the stations, the principal or

single peak being in pebbles except at Llandewey where it is in cobbles. The secondary maximum is in silt or sand.

Cross sections of the Yallahs River at stations located a few kilometers apart along the entire length of the channel were surveyed as in the case of the Buff Bay River. Six of these stations were selected for the determination of hydraulic geometry of the Yallahs River. The rates of change of width, depth, and velocity with increasing discharge at these locations are summarized in table 3.

The rate of increase of width with increasing discharge (b) is high. Concomitantly the rate of increase of depth (f) is low in contrast to the findings from the Buff Bay River. The larger value of at-a-station b over f reflects the wide dish-shaped channel of the Yallahs River shown on the cross sections (Leopold, Wolman, and Miller, 1964) in contrast to the more box-like channels in the Buff Bay.

The Mavis Bank figures, however, show a departure from the general tendency along this river. At Mavis Bank, the exponent f is much higher than b, and the highest value of m (0.45) is observed. The Mavis Bank station was set up close to a gage in an attempt to correlate the field data with the recorded flow. In the immediate vicinity of this station the Yallahs is not braided, and this reach is a single channel, in between the upstream junction of two anastomosing channels and downstream separation of two such channels. Here the river tends to be narrow and comparatively deep in the immediate vicinity of the station, explaining the anomaly in the data.

Values of exponents b and f were plotted against exponent m (fig. 7) for the 6 stations on the Yallahs River. A station with a rapid change in velocity with rising discharge is associated with a low rate of change of width, as at Mavis Bank. In such cases, the rapid change in velocity is also associated with a rapid increase in depth. This is expected as increasing depth and decreasing relative roughness should result in increasing velocity. On the other hand, a river that adjusts to a greater discharge by widening the wetted cross section rather than deepening it would have a low rate of increase in velocity. This relationship is described by a direct correlation between f (where depth varies as  $Q^f$ )

TABLE 3  
Variation of at-a-station hydraulic characteristics  
The Yallahs River

Station	Drainage area km <sup>2</sup>	No. of observations	Value of exponents			
			b	f	m	b+m+f
Potsdown	22.20	6	0.84	0.06	0.09	0.99
Mavis Bank	25.30	6	0.04	0.60	0.45	1.09
Mahogany Vale Footbridge	55.32	4	0.38	0.38	0.26	1.02
Ramble	105.52	5	0.31	0.32	0.28	0.91
Llandewey	123.28	5	0.51	0.29	0.16	0.96
Easington	136.41	5	0.48	0.27	0.23	0.98

Source: Field observations.

and  $m$  (where velocity varies as  $Q^m$ ) and an inverse one between  $b$  (where width varies as  $Q^b$ ) and  $m$ , as in figure 7. Superimposition of the field of Buff Bay data on figure 7 shows that for a comparable change in velocity, the Buff Bay goes through a greater change in depth and a smaller change in width than the Yallahs River.

THE BUFF BAY AND YALLAHS: A COMPARISON

Table 4 compares the two rivers indicating the primary difference in channel pattern and form. The Yallahs is a braided river except where it cuts through narrow gorges in straight reaches. The characteristic channel shape is rectangular, wide, shallow, a flat-bottom stream with steep banks. With rising discharge the channel gets comparatively wider not deeper. In contrast, the Buff Bay River meanders through most of its length with occasional straight reaches in the headwaters section, where it flows over locally steep gradients. The channel is deep, round-

TABLE 4  
Comparison of the Yallahs and Buff Bay Rivers

Factors	Yallahs	Buff Bay
1. Channel pattern	Braided or straight	Meandering or straight
2. Channel shape	Wide shallow flat-bottomed channel with steep banks	Deep round-bottomed channel with sloping banks
3. At-a-station change in channel with rising discharge	Rate of change in width with increasing discharge greater than simultaneous rate of change in depth	Rate of change in depth with increasing discharge greater than simultaneous rate of change in width
4. Depositional features	Mid-channel bars and sidebars	Point bars and large, high, vegetated islands in lower reaches
5. Bed material	Coarse and at least half of the river bimodal. Principal mode—pebbles and cobbles. Secondary mode—silt or sand (when present)	Coarse and bimodal. Principal mode—pebbles or cobbles. Secondary mode—sand
6. Bank material	Similar to bed material in texture. Weak fining upward sequence at places. Locally imbrications in pebbles.	Very shallow layer of silt and sand on top. Rest similar to bed materials. No significant structures observed.
7. Tributary junction		
A. Tributary same size as main stream	Both go over rapids before joining and deposit coarse part of bedload prior to joining	Accordant tributary junction
B. Tributary not much smaller than main stream	Accordant tributary junction	Accordant tributary junction
C. Tributary much smaller than main stream	Tributary tends to hang and is accordant with the floodplain, not the channel of the main stream	Accordant tributary junction
8. Floodplain height above channel bed	90 to 100 cm	90 to 180 cm
9. Low Terrace height above channel bed	280 to 400 cm	300 to 480 cm

bottom, with sloping banks, and with rising discharge the depth increases at a faster rate than the width. The difference between the two rivers may also be clearly shown by drawing a series of channel cross sections, spaced about 30 m apart, on both streams for reaches with varying lithology and total annual rainfall. This was done, and in spite of variations in lithology and annual rainfall, such sections on Buff Bay clearly indicate the meandering pattern and box-like shape separating it from the Yallahs sections illustrating the braided pattern and dish-like appearance throughout (Gupta, ms).

Starting from the assumption that a landform is a function of structure, process, and probably time, depending on ones bias, it may safely be stated that the appearance and behavior of a stream is an outcome of its environment. Since all eastern Jamaica was exposed to sub-aerial denudation roughly at the same time (Zans and others, 1962; Robinson, Lewis, and Cant, 1972), we may eliminate time from consideration and concentrate on the other factors, structure in the Davisian sense and geomorphic processes.

As table 1 indicates the environments of the two rivers are broadly similar with the only significant exception, rainfall regime. We may also recollect that the Buff Bay and the Yallahs are not unique but representatives of stream types found on the two slopes of the Blue Mountains. Reconnaissance field visits to the river valleys on the north and south slopes of the Blue Mountains revealed that all streams on one side of the mountain display characteristics typical of that slope, in spite of the fact that the annual rainfall on each side decreases prominently from east to west. For example, the Buff Bay is similar to the Wag Water (fig. 1), the precipitation in the valley of the Wag Water being lower and about the same as in the Yallahs valley. On the other hand the characteristics of the Buff Bay are also common in the channel of the Rio Grande in the east which flows through a much wetter terrain, receiving rainfall between 350 and 640 cm annually. Absolute increase in total rainfall in this tropical humid area does not alter the stream characteristics, but the difference in regime seems to be linked on empirical evidence with the difference in channel pattern. Rivers like the Yallahs flowing through the wet-dry seasonal climate of southeastern Jamaica produce the braided pattern. This is further substantiated as the Yallahs changes shape near Jacob's Bridge (fig. 6), where the data in figure 5 indicate that seasonal effects become significant.

Tropical areas with a seasonal rhythm in precipitation are usually areas with wide shallow rivers, often braided, where at the end of the "wet" period the rivers shrink to low flow channels leaving vast expanses of wet alluvial flats to dry in the sun. Such rivers, for example, have been noticed in Monsoon India. Seasonality in precipitation and shallow braided channels are empirically interlinked. Understanding of the linkage, however, is not quite apparent, the difficulty being partly due to the fact that several factors have been suggested in the literature to explain either meandering or braided channels. For example, co-

hesiveness of the bank materials, nature of discharge, combination of gradient and discharge, et cetera, all have been used to explain the meandering pattern. Similarly braided streams have been caused by the presence of abundant and coarse load, rapid and large variation in discharge, abrupt change in stream gradient, considerable bank erosion, and combination of gradient and discharge. Braiding results from overloading to the point of aggradation and splitting of a single channel into multiple smaller ones. The explanation is associated with the inability of the stream to transport the sediment supplied to the channel. Seasonality in discharge apparently would lead to an episodic nature in the work done by the stream. With rising flow in the "wet season" a river would occupy the entire channel, and bank erosion, sediment transport, et cetera, would be vigorously carried out. In the "dry season" with the river shrinking to a fraction of its former size, almost the entire sediment in transport would be deposited within the channel to build bars. Having insufficient flow to accomplish any work the river would display a shallow braided appearance until the next "wet season" when the sediment stored within the channel would travel again. Due to lack of vegetation and humus on these temporary bars the sediment would be loose and easily erodible. Coarseness of texture would further heighten the effect. The contrast in ability of the river to erode and transport in different seasons is probably responsible for the wide, shallow braided streams in regions of seasonal precipitation.

#### OCCURRENCE OF LARGE FLOODS IN THE YALLAHS AND BUFF BAY VALLEYS

High-magnitude rainfall as mentioned previously occurs on a regular basis in this area. Given the high relief, steep slopes, thin soil cover, and absence of the original forest vegetation, run-off is quick and high, and the rivers rise in floods creating a set of characteristic valley forms. A discussion of the Yallahs and Buff Bay Rivers should include references to these features over and above the more common forms discussed in previous sections. Quantitative information regarding the magnitude of these catastrophic floods is difficult to come by as gaging station records are either not long enough or not obtained during past high floods. Some measures of flood size may be estimated from field observations, information gathered from local people, reports in the *Jamaica Weather Report*, and descriptions in the *Daily Gleaner*. One can state whether the water was barely over the floodplain, deep over the floodplain, or inundated the low terrace. At least 16 major floods occurred between 1900 and 1972, about half of which were high enough to submerge even the low terrace. A major flood in which water flows about 1 m deep on the floodplain and is bounded by the rise to the low terrace surface occurs on the average in these valleys once every 4.5 yrs. The low terrace surface is submerged roughly once every 10 yrs.

Several measurements and estimates of floods, however, are available. A gauge at Fellowship on the Rio Grande survived the hurricane Flora flood in October 1963, and the computed daily discharge was

624 m<sup>3</sup> sec<sup>-1</sup> from a drainage area of 214.9 square km or 2.9 m<sup>3</sup> sec<sup>-1</sup>/km<sup>2</sup>. The Rio Grande is located only about 25 km east of the Buff Bay River, and floods of similar magnitude might have occurred in the latter valley. The probable maximum flood for the Buff Bay as calculated by Harza and Chin (1971) based on a probable maximum cloudburst storm of 6 hr duration has a peak discharge of 44 m<sup>3</sup> sec<sup>-1</sup> per square km. For the Yallahs River "no major floods have been gauged and the only quantitative data found are that marked on a P.W.D. drawing of the Mahogany Vale Footbridge which was built in 1914 after the original structure has been washed away in 1909" (Howard Humphreys, 1967, I, p. 17). From the channel profile and bed gradient, using a Manning's n of 0.08, calculated peak discharge is 37.3 m<sup>3</sup> sec<sup>-1</sup> per square km (Howard Humphreys, 1967). A 30-year flood has been estimated by the same source to have a peak discharge of 22 m<sup>3</sup> sec<sup>-1</sup> per square km on the Yallahs at Mamogany Vale. A network of stream gauges is being established in Eastern Jamaica, and the future record from these may turn out to be extremely interesting.

#### FLOOD EFFECTS IN THE YALLAHS AND BUFF BAY VALLEYS

*Size of flood deposits.*—The entire valley floors of the narrow river valleys of Eastern Jamaica are affected by the onrush of floodwaters. Given the size of the floods and the steep gradient of the Blue Mountain streams, the channels are competent to transport very coarse bedload during floods. On walking the streams one is impressed by the scattered boulders much larger than the rest of the sediments. Boulders with an intermediate diameter between 1 and 2 m are common, and the largest boulder found measured 5.5m to 4.9m to 3.7m.

Assuming that during the floods the entire flow is turbulent, it is possible to calculate the tractive force of the flood of a given height using Shield's entrainment function

$$\frac{\tau_o}{d \gamma (S_s - 1)} = 0.056 \text{ (Henderson, 1966)}$$

where  $\tau_o$  = shear stress at the bed,  
 $d$  = the grain diameter,  
 $\gamma$  = specific weight of water, and  
 $S_s$  = solid-fluid density ratio.

Substituting depth of flow  $y$ , for  $R$ , the hydraulic radius  $\tau_o = \gamma y S$  where  $S$  is the slope of the channel. Solving for  $d$ , the grain diameter and assuming  $S_s = 2.65$ , we get  $d = 11yS$ . Knowing the slope, the depth needed to move boulders of a given size can be determined. Using this equation the maximum depths of water needed to move boulders of a given size along the two rivers have been calculated (Gupta, ms).

While the computations involve a number of assumptions and are by no means precise, they do indicate that these rivers in flood would be expected to move very coarse materials. In the last hurricane which

occurred during October 1963 and for which depth estimates were made, 4.5 m peaks were achieved in both the Buff Bay and Yallahs, indicating competence up to 1 m, exact size depending on local gradient. Peaks during floods like the one in 1909 from the highest rainfall recorded on the Blue Mountains could have been even higher. After the October 1963 flood, boulders were discovered lying on the surface of the Coast Road at the Yallahs Fording (Robinson, personal commun.). Floods caused by hurricane rains seem to be sufficient to move even the biggest materials found in these channels, and hence they are not relicts from a past environment. Scouring of sand and pebbles surrounding a boulder may dislodge it at a lesser velocity than critical tractive velocity, and once in motion the boulder may travel for some distance under its momentum and because a velocity less than the critical tractive one is sufficient to keep the boulder in motion. The large boulders have been contributed to the channel by landslides, and they also might have travelled for some distances under the momentum achieved by falling off the mountains. At certain places boulders coming off a landslide have reached the foot of the opposite hillslope by bounding across the width of the valley. Some of the stations include one or two boulders that need an uncommon depth to attain a critical shear stress. This might have been achieved in a very large flood any time since the early Holocene when the present valley fill was laid down (Gupta, ms).

Materials smaller than boulders would be easily transported in these high floods. Cobbles and pebbles forming almost the entire channel may be eroded from the bed, bank, and bars, carried downstream, and re-deposited at sheltered places during the falling stage of the flood. The flood in October 1963 was high for about a week, as reported by local inhabitants and in newspapers. During this period a considerable amount of the detritus should reach and rebuild the fans near the mouth of the rivers and even reach the Caribbean Sea. Submarine cables were broken offshore near the mouths of the Yallahs and Hope Rivers during the 1963 hurricane suggesting the nature of sediment pouring off the island shelf (Burke, 1967). Even floods of smaller magnitude, for example, one in November 1970 on the Buff Bay River with a recurrence interval of 3.6 yrs, moved boulders about 0.5 m in diameter (Beale, C. D., personal commun.).

*The flood originated forms.*—The most conspicuous valley form is the low terrace, which stands about 1.75 to 3 m above the floodplain and is differentiated from it by a nearly vertical riser. The top surface is made irregular by big flood channels and mid-channel bars. Such bars at places could be as high as 2.4 m on the terrace surface. The low terrace abuts either the foot of the local and yet unexplained 9 m high terrace found in the valleys of the Yallahs or Buff Bay or the steep hills bounding the valley floor. The distribution of the low terrace is shown in figure 8.

The terrace is made of coarse materials, mostly subangular to sub-rounded pebbles with some sand, cobbles, and boulders ranging up to

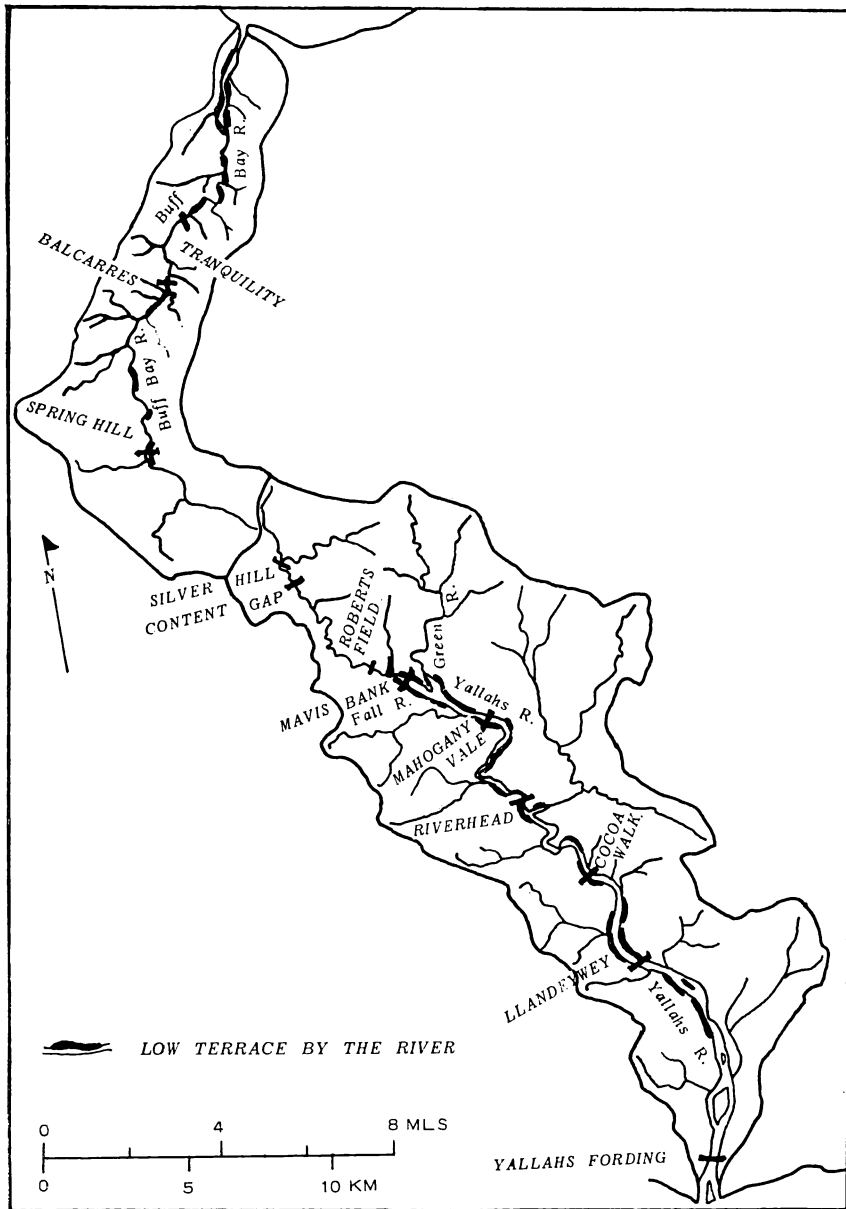


Fig. 8. The low terrace in the Yallahs and Buff Bay Valleys.

1 m. The deposits may occur as thin (8-18 cm) alternating layers of coarse sand and fine pebbles or as a meter of sand over several meters of imbricated pebbles. Within a thick pebble layer, a weak fining-upward sequence may be discerned. The only sedimentary structures seen were the generally prevalent imbrication in the pebbles and indistinct laminations in silt when on rare occasions silt is present.

A layer of pebbles cover the terrace surface. Only when flood channels have been cut into the terrace deep enough for frequent floodwaters to flow into such channels is a top silt layer found. Elsewhere even when the top part of the terrace is made of sand, it is protected by a pebble armor, the thickness of which is about 6 cm, or roughly, the diameter of a single pebble. It might be pointed out that such a pebble cover is also found on floodplains and channel bars. Sand bar deposition has been observed in the Green River close to its confluence with the Yallahs during a bankfull flood. A subsequent visit showed that the sand bar has acquired a surface armor of fine pebbles presumably by winnowing of the fines. Such armor tends to provide a remarkably flat surface and protects the underlying soft materials from erosion except during high floods.

A distinct vegetation pattern occurs on top of the low terrace. Thorny scrub trees about 3 to 4.5 m high contrast with the bare floodplain on one side, and tall trees and dense undergrowth on the hillslopes or high terrace on the other. The scrubby trees are of comparable height, appear to be extremely young, and of species different from those in higher parts of the valley. The number of the species on the terrace is also restricted. The most common trees are acacias, chiefly *A. macracantha* and *A. villosa*, and West Indian Ebony (*Brya ebenus*), to which some cacti and other xerophytic plants are added in the drier parts of Eastern Jamaica through which the lower Yallahs flows.

Since the trees all appear to be of the same stature, attempts were made to determine their age. Tree rings in seasonal tropics are unreliable and instead girth measurements below branching were used. From measurements taken during May 1971 the trees (*Acacia villosa* and *Brya ebenus*) seem to be between 3 and 7 yrs old with 5 being the most likely age (Adams, personal commun.). The last hurricane flood to affect this area was in October 1963 about 7½ yrs before the date of sampling. Apparently the trees are all post-1963 hurricane flood, which must have destroyed the pre-flood vegetation. During the high magnitude floods with about 4.5 m of water flowing in these valleys, these terraces of pebbles and cobbles are considerably modified as critical tractive forces are sufficient to move boulders even 1 m in diameter. Rebuilt terraces emerge with the falling flood level, and between two such huge floods terrace surfaces may be colonized by plants different from vegetation in higher parts of the valley and bordering hillslopes.

There is a relationship between the low terrace and high magnitude floods that periodically inundate the valley bottoms. However, it is still not quite clear whether the origin of these terraces is associated with

flood deposition. The present appearance of the low terrace has been created by the tremendous onrush of the water in the 1963 hurricane Flora flood, but local information indicates tree-covered terraces existed before 1963 in the valleys. The material forming the terraces comes chiefly from landslides and other processes of denudation upstream, and the locale of deposition depends on the width and slope of the valley. The low terrace is absent in gorges. We may surmise that the low terrace was first created by an early high magnitude flood after the drainage net was excavated in the Blue Mountains, and once formed, such terraces have been repeatedly eroded, the materials removed, and similar material carried down from upstream deposited to *rebuild* the terrace at old locations during high magnitude floods. Thus the terrace is not strictly speaking a relict of the past but owes its continuing existence to the periodic and relatively frequent recurrence of the large floods.

*Sequence of events during floods.*—The following sequence of events is postulated from observations in the field and from the historical and botanical information.

1. The coarse valley fill is one source of detritus for transport by the rising floodwaters. This is augmented by extensive landslide debris falling into the swollen river.

2. The high flood at peak or near peak stages covers the valley floor to a depth of about 4.5 m. If locally the valley is rather wide, as the Yallahs Valley near Fall River, the highest parts may not be inundated as shown by the higher and older trees surviving and by the absence of any flood signs in these parts of the valley floor. During the flood river course changes may, however, take place in such wide reaches as shown by old scoured channels.

3. During the time the valley floor is inundated, about a week in October 1963, materials ranging up to boulder size are eroded, transported, and redeposited farther downstream. (Similar deposition of coarse materials downstream was described by Stewart and LaMarche (1967) during a 100-yr flood in the valley of the Coffee Creek, Calif.). Vegetation in the low terrace was destroyed.

4. A wide channel is excavated in the valley, roughly equal to the width of the sum of the present floodplain and channel. During a high flood this is probably cleared of all sediments but large boulders. Widening of channels in floods has also been reported in other case studies (Hack and Goodlett, 1960; Gupta and Fox, 1974).

5. Floods of lesser magnitude deposit within this widened channel, building a floodplain at the foot of the terrace and shrinking the channel to its normal size. Deposition also takes place within the channel around boulders to rebuild mid-channel bars in the Yallahs, and low flow channels are excavated round them during the dry period. In case of the Buff Bay River, within-channel deposition is in the form of point bars as befitting a meandering stream.

Review of some of the flood events described in the literature (Wolman and Eiler, 1958; Hack and Goodlett, 1960; Stewart and LaMarche,

1967) reveals the principal effects on the landscape as destruction of vegetation, landslides, deposition of coarse detritus in the valley, and widening of channels. Hack and Goodlett (1960) also described a terrace-like feature 3 to 6 m above the floodplain. This high feature is usually under vegetation which hides the flood effect as the catastrophic floods occur in the Central Appalachians perhaps once in 100 yrs. On the other hand, in the mountains of Eastern Jamaica comparable large floods may occur once in about 10 yrs. As a result the scars on the landscape are never healed, and the terrace surface is always visible.<sup>2</sup> In fact the terrace surface might even be considered as a 10 or 15 yr floodplain or a hurricane floodplain of the rivers. This form is modified and rebuilt by lateral erosion of the floodwaters across the entire valley floor. Below this level, there is the normal floodplain inundated approximately once in 2 yrs, and the lowest part of the valley contains the channel of the river.

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<sup>2</sup>A. W. Kemp (personal commun.) mentioned formation of a terrace in a high flood in the valley of the Stony River within the Morant watershed in the Blue Mountains. This terrace was built between two visits to this valley, one before and the other after the flood. Such terraces are visible in almost all valleys in the Blue Mountains.

## REFERENCES

- Adams, C. D., 1971, *The Blue Mahoe and Other Bush*: Singapore, McGraw-Hill F.E.P., 151 p.
- , 1972, *Flowering Plants of Jamaica*: Mona, Univ. West Indies, 848 p.
- Andrew, E. M., 1969, Seismic surveys over river gravels in Jamaica, May-August, 1964: London, Overseas Geol. Surveys, Geophys. Rept. 28.
- Burke, K., 1967, The Yallahs Basin: A sedimentary basin southeast of Kingston, Jamaica: *Marine Geology*, v. 5, p. 45-60.
- Cant, R. V., ms, 1971, Aspects of the Geology of the Pleistocene Marine Terraces of Jamaica, W.I.: Ph.D. dissert., Univ. West Indies, Kingston.
- Gupta, A., ms, 1973, The effect of Seasonal Flow and High Magnitude Floods on Channel Form and Stream Behavior in Eastern Jamaica: Ph.D. dissert., Johns Hopkins Univ., 289 p.
- Gupta, A., and Fox, H., 1974, Effects of High-Magnitude Floods on Channel Form: a case study in Maryland Piedmont: *Water Resources Research*, v. 10, p. 499-509.
- Hack, J. T., and Goodlet, J. C., 1960, Geomorphology and Forest ecology of a mountain region in the Central Appalachians: U.S. Geol. Survey Prof. Paper, 347, 66 p.
- Harza Engineering Co., and Hue Lyew Chin, 1971, Streamflow in the Yallahs River, the Blue Mountain water supply project for the Government of Jamaica and the Water Commission: June, Kingston, Jamaica, 17 p.
- Henderson, F. M., 1966, *Open Channel Flow*: New York, MacMillan, 522 p.
- Howard Humphreys and Sons, 1967-1968, *The Yallahs River Water Supply Scheme, Feasibility Study for the Government of Jamaica and the Water Commission*: Kingston, Ministry Overseas Devel., v. 1-4.
- Kemp, A. W., ms, 1971, *The Geology of the Southwestern Flank of the Blue Mountains, Jamaica*: Ph.D. dissert., Univ. West Indies, Kingston.
- Leopold, L. B., and Maddock, T., Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geol. Survey Prof. Paper 252, 57 p.
- Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, *Fluvial Processes in Geomorphology*: San Francisco, Freeman, 522 p.
- Lirios, J. F., 1969, Rainfall intensity-duration-frequency maps for Kingston and St. Andrew, Jamaica: *Caribbean Met. Ins.*, mimeographed.
- Paget, E., 1956, *Land Use and Settlement in Jamaica: Geographical Essays on British Tropical Lands*: London, George Philip & Sons, 344 p.
- Robinson, E., Lewis, J. F., and Cant, R. V., 1972, *Field Guide to Aspects of the Geology of Jamaica*, in I.F.I. Guidebook to the Caribbean Island-Arc System, 1970: Washington, Am. Geol. Inst.
- Stewart, J. H., and LaMarche, V. C., 1967, Erosion and Deposition produced by the floods of December 1964, on Coffee Creek, Trinity County, California: U.S. Geol. Survey Prof. Paper. 422-K, 22 p.
- Vickers, D. O., 1967, Very heavy and intense rainfalls in Jamaica: Univ. West Indies Conf. on Climatology and Related Fields, Mona, W.I., 1966, Proc., p. 57-63.
- Wolman, M. G., 1954, A method of sampling coarse river-bed material: *Am. Geophys. Union Trans.*, v. 35, p. 951-956.
- Wolman, M. G., and Eiler, J. P., 1958, Reconnaissance study of erosion and deposition produced by the flood of August 1955, in Connecticut: *Am. Geophys. Union Trans.*, v. 39, p. 1-14.
- Zans, V. A., Chubb, L. J., Versey, H. R., Williams, J. B., Robinson, E., and Cooke, D. L., 1962, Synopsis of the Geology of Jamaica: Kingston, Jamaica Geol. Survey Dept., Bull. 4, 72 p.