Chapter 7

SOILS OF THE UPPER RÍO CHAGRES BASIN, PANAMA

Soil Character and Variability in Two First Order Drainages

J. Bruce J. Harrison[1], Jan M.H. Hendrickx[1], David Vega[2], Lucas E. Calvo-Gobbetti[2]

[1]*New Mexico Institute of Technology,* [2]*Universidad Tecnológica de Panama*

Abstract: Understanding the relationship between rainfall, and stream flow in mountain terrain requires the quantifying of rates of water movement into and through regolith covered hillslopes. General theory holds that infiltration rates in humid tropical are higher than rainfall intensities so surface runoff is minimal. However, soil profile characteristics can vary significantly on a hilslope, with concomitant changes in soil hydrologic characteristics. The pattern of soils within two small first order drainages was evaluated within the upper Río Chagres basin. Two main influences on soil distribution were identified. Mass movements primarily translational sliding and treefall result in stripping of the upper soil horizons and exposure of weathered saprolite. Soils forming in the deposits are characterized by higher infiltration rates and a more uneven surface topography than the stable soils. A catenary relationship was also observed with stable, oxidizing soil profiles in upper slope positions and reduced (gleyed) soils at the outlet of the drainage basin.

Key words: Panama; Río Chagres; tropical soil catenas; saprolite; mass movements

1. INTRODUCTION

A fundamental question when studying streamflow in tropical and humid environments is the role that hillslope characteristics play in determining streamflows. The hydrologic properties of soils developed in the unconsolidated regolith in first order drainage basins can have a major influence on how rainfall is translated into steamflow. If the infiltration rate of the soil is low, then surface runoff becomes a major factor in streamflow response to rainfall (Ridolfi *et al.,* 2003). By contrast, if the infiltration rate on steep hillslopes is high, then subsurface flows will be an important component of streamflow (Montgomery and Dietrich, 2002). Within the soil

R. S. Harmon (ed.), The Río Chagres, Panama, 97-112.

profile, the depth to bedrock or a less permeable layer and the soil porosity become important factors influencing water movement through the regolith and into the stream channel.

Detailed measurements of soil hydrologic properties are time consuming and only represent a point estimate of hydrologic properties of the soil. The hydrologic properties of a hillslope result from an integration of the hydrologic properties of the different soil units on the hillslope. Thus, it is important to characterize the range of hydrologic properties on a hillslope and to determine the proportion of the drainage basin hillslope characterized by the individual soil units. Measured infiltration rates on hillslopes in the Luquillo Mountains of Puerto Rico ranged from 0-106 mm/hr (Harden and Scruggs, 2003), which largely exceeded the rainfall rates in this area. However, no estimate was made of the proportion of the hillslope characterized by each infiltration measurement. Determining the spatial variation of soils on a forested hillslope is also a time consuming and difficult process. There are logistical constraints to developing a statistically significant, randomly sampled, data set of soil hydrologic properties within a drainage basin. One approach to determining variability of soil properties is to identify the major controls on the spatial variability within the drainage basin. From this starting point, it is possible to locate soil sampling sites in a pattern which will encompass the major range of soil profile characteristics.

Hillslopes can be broadly classified as stable or unstable systems. Unstable hillslopes occur in geomorphically active drainage basins, where patterns of erosion and deposition are reflected in the distribution of eroded and buried soil profiles. The pattern of soil variability is determined by pattern of erosion and deposition and the degree of soil development is determined by the age of the land surface. This has been described as temporal soil variability (Tonkin, 1993).

On stable hillslopes, topography produces systematic changes in soil profile characteristics with the two main influences being slope orientation and the position of a soil profile within the drainage basin. Slope orientation results in differences in solar radiation and/or exposure to eolian or atmospheric deposits of dust or salts. (Birkeland, 1999). On stable hillslopes, throughflow in the regolith produces systematic changes in soil properties in the direction of water movement. Usually, soils in upper slope positions are more leached than soils in lower slope positions because they are not receiving any replenishment from upslope soils. However, while major differences in soil morphology can be determined, the boundaries between the different soils are usually gradual (Young, 1988). This pattern of soil variability has been described as a soil catena. (Milne, 1935; Birkeland, 1999). Thus, the pattern of soil distribution is different according to whether the drainage basin is stable or unstable. The goal of the soil studies in the

4. OBSERVATIONS AND RESULTS

The drainage basins have similar morphologies; both are small, narrow, and steep. The Río Chagrecito basin has a 2 m scarp at the head of the basin, where it connects to the dissected ridge. Saprolite is exposed at the base of the scarp. The upper Río Piedras drainage lacks a scarp at the head of the basin. However, the soil at this point in the drainage is shallow and weakly developed. Both drainages have irregular downslope topographic profiles, with up to 2 m of relief developed through mass movements. The mass movement erosion scars expose saprolite, indicating that the failure plane occurs at the soil/saprolite boundary. Erosion scars are widespread along the upper slopes of the drainage. but almost totally lacking in the lower part of the drainage. Trees are rafted in an upright position downslope with mass movements so that it is often difficult to identify areas of mass movement. Large cracks at the soil surface in both drainages appear to be tension cracks related to the mass movements.

Treefall is a common feature in both drainages, but occurs more frequently on the ridge crests into which the drainages are developing. This process produces a pit and mound topography, which can create a preferred pathway for water to enter a soil (Schaetzl *et al.,* 1990).

4.1 The Río Chagrecito Study Site

The first order drainage basin studied along the middle reaches of the Río Chagrecito is at an elevation of 1391 m. It is 150 m from ridge crest to the point of free flowing water, and approximately 50 m wide. The drainage is developed in deeply weathered granitic bedrock. Slope angles range from 55° at the head of the basin to 20 ° at the toe of the slope. Soils from three sites were described down the axis of this first order drainage basin. The relative thickness and horizonation of each soil profile are shown in Figure 1 and compositional characteristics of the three soils examined are listed in Tables 1 and 2.

The Chagrecito-1 soil is from the edge of an erosion scarp near the ridge crest. This soil is strongly developed and overlies deeply weathered bedrock or saprolite (Fig. 2a). It has a thin A horizon and several B horizons of clay and iron accumulations that grade into saprolite at 3 m depth. A large pipe, probably an old root channel, at 30 cm depth is lined with dark humus and clay coatings. The soil has a coarse angular blocky structure in the upper part of the profile, with large soil ped faces coated with humus and clay. This soil is very fine textured, containing less than 10 % sand and having high silt and clay contents. There is a marked change in the texture at the soil/saprolite contact where the sand and clay contents decrease and the silt content of the profile increases significantly (Table 2).

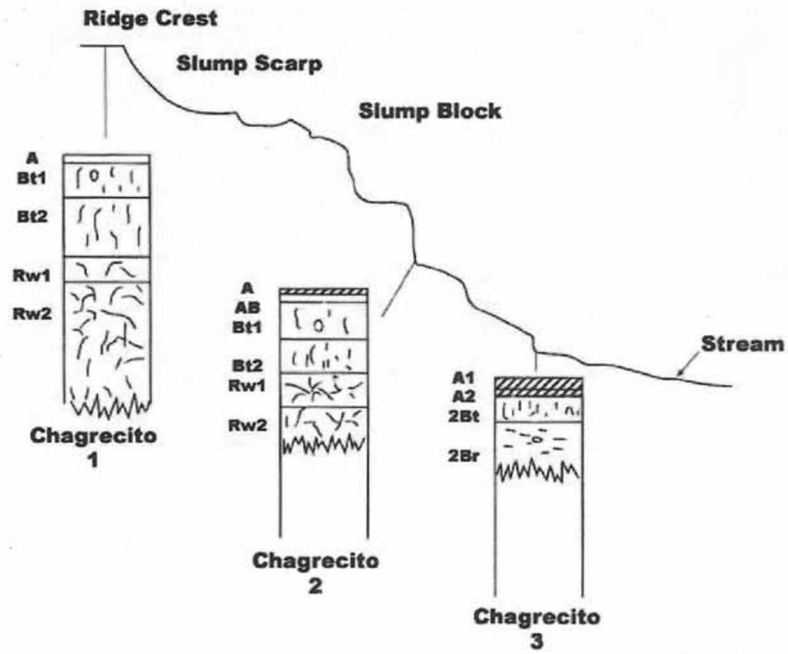

Figure 1. Diagrammatic representation of the Río Chagrecito soil profile locations.

The Chagrecito-2 soil (Fig.2b) is from a midslope in an area of uneven surface topography. It has a similar A horizon to the Chagrecito-1 soil, but the B horizons are not as strongly developed. This soil contains more weathered clasts and has less red coloring than the Chagrecito-1 soil. A coarse blocky structure occurs in the top 60 cm, with humic and clay coatings on ped faces. The sand content of this profile is higher and the clay content a little lower than in the Chagrecito-1 soil (Table 2).

The Chagrecito-3 soil is developed at the base of the hillslope. It has a very weakly-developed A horizon and contains gravely B horizons. The presence of gleyed colours and iron oxide concretions indicates that a reduced soil environment exists for periods of time during the year (Fig 2c). As this soil was being described, water was flowing from pores and old root channels (Fig 2d). This soil has the highest sand content and a lower silt content than the other soils in this drainage (Table 1).

upper Río Chagres drainage basin described here was to determine the controls on soil variability and to identify the range and spatial extent of soil profiles present.

2. TROPICAL SOILS

The distinct features of tropical soils are a reflection of the moist warm climate typical of tropical regions of the world. This climate promotes strong weathering resulting in the formation of deeply weathered bedrock or unconsolidated regolith termed saprolite. The strong weathering environment results in a soil with a high clay content, with the common mineralogy being kaolinitic, and enriched in the more residual elements such as Fe, Si, and Al. Organic matter levels are usually low, often only a thin organic layer is found at the soil surface and low (<4%) organic carbon is found within the soil profile. These soils usually are classified within the Oxisol and Ultisol orders of the USDA soil taxonomy (USDA, 1994).

3. METHODS

The upper Río Chagres watershed is a strongly dissected, densely forested landscape with most hillslopes bearing first and second order streams. Two small first order drainages were chosen for detailed soil studies, one developed on a granitic lithology in the upper portion of the Río Chagrictio drainage and the other in altered rhyolite in the upper reaches of the Río Piedras drainage (see Fig. 1 of the Preface for the site locations).

Soil pits were described down the axis of the drainage, from the intersection of the drainage basin with a main ridge, down to where a perennial stream issued from the regolith. Pits were hand dug into the underlying saproloite to a depth of at least 50 cms. Soils were described following the standard procedures (USDA, 1993). Samples were taken from every pedogenic horizon and, where the horizon was greater than 20 cm thick, sampled at 20 cm intervals. Subsequently, each soil sample was analyzed in the laboratory. Particle size was determined using the pipette method and bulk density by the paraffin clod method (Singer and Janitzky, 1986). The clay mineralogy was determined for selected samples, which covered the range of weathering observed in the field. Infiltration studies were carried out at different depths for each of the soils described here by Hendrickx *et al.*, (2005, this volume).

Table 1. Morphological description of Chagrecito site soils.

Soil	Slope Position	Horizon	Color (moist)	Depth (cm)	Texture	Structure	Consistency (dry)
CH-1	crest						
		litter		5-0			
		A		0-5	SiCl	3mcr	h
		AB		5-10	Cl	3lsbk	h
		B1		10-50	Cl	3msbk	h
		B2		50-120	Cl	M	vh
		Rw		120-150	SiCl	M	h
		Rw2		150-300	SiL	M	sh
CH-2	back	litter		5-0			
	slope	A	7.5YR3/3	0-5	SiClL	3msbk-3Lcr	sh
		AB	7.5YR4/6	5-15	Cl	3msbk-3Lcr	h
		B1	5YR4/6	15-60	Cl	3msbk-3Lcr	h
		B2	5YR5/6	60-100	Cl	3msbk-3Lcr	
		Rw1	2.5YR4/8	100-140		M	
		Rw2	10YR5/6	140-280+		M	
CH-3	foot	Litter		5-0			
	slope	A1	10YR4/4	0-10	Cl	3msbk	h
		A2	10YR4/3	10-20	grSCl	2msbk	sh
		2B1	2.5YR6/1	20-50	Cl	3msbk	h
		2B2	5BG4/6	50-100+	Cl	3msbk	h

Soil	Slope Position	Consistency (moist)	Roots	Pores	Comments
CH-1	crest				
		ss,sp	3vf,f,m,l	2l	pores 5-6 cm diam
		s,p	2vf2f2m1l		large cracks
		s,p	1vf1f2m		large cracks
		s,p	1vf1f1m1l		large root burrows
		s,sp	1f1m		transition to saprolite
		nsnp	1vf1f		
CH-2	back				
	slope	ss,sp	3vf3f3m	3f2m	animal burrows,
		s,p	1vf2f2m	cracks+2L	35%wk-st w'd clasts
		s,p	1vf2f1m	cracks 1m	10%wk w'd rocks
		s,p	1f1m	10-0.5cm pores	
					strongly weathered bedrock (saprolite)
					strongly weathered bedrock, more homogeneous color than above)
CH-3	foot				
	slope	s,p	1vf2f	large cracks	
		s,p	2vf2f1m	3m	
		s,p	2f2m1l	5cm pipe, cracks	
		s,p	2f2m1l	pipes and cracks	strongly gleyed, mottled

Figure 2a. Chagricito-1 soil.

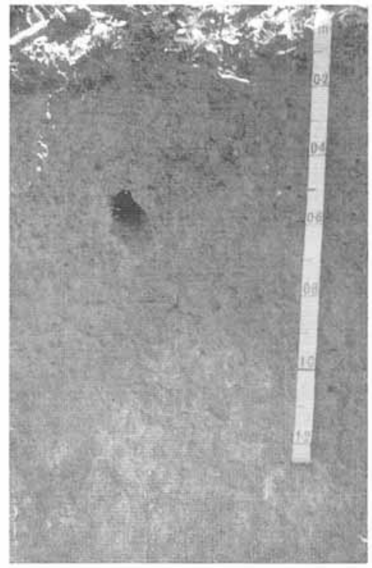

Figure -2b. Chagricitó-2 soil.

Figure 2c. Chagricito-1 soil.

Figure 2d. Water flowing from former root channel in Chagrecito-3 soil.

Table 2. Particle size and bulk density data for the Chagrecito site soils.

Soil	Slope Position	Horizon	Bulk Density (g/cm^3)	Sand %	Silt %	Clay %
CH-1	crest	Litter				
		A	1.2	9.1	67.9	23
		AB	1.3	7.8	54	38.2
		B1	1.36	5.9	53.6	40.4
		B1	1.4	6.1	57.8	36
		B2	1.38	6.4	59.7	33.8
		B2	1.45	6.7	44.4	48.8
		B2	1.45	4.7	52	43.4
		RW1	1.47	6	61	32.9
		RW1	1.4	8.9	87.6	3.5
		RW2	1.3	9.2	68.9	22
		RW2	1.25	9.2	72.8	22
		litter				
CH-2	backslope	A	1.21	16.7	67.9	15.4
		AB	1.27	15.4	63.2	21.4
		B1	1.38	16.9	65.1	18
		B2	1.5	14.5	72.4	13
		Rw1	1.38	11.1	71.8	17.1
		Rw2	1.2	15	70.8	14.2
CH-3	footslope	Litter		25.6	67	8
		A1		42.3	40.9	17
		A2		48.2	35.1	16.7
		2B1		9.2	68.8	22
		2B2		14.6	69.7	15.7

4.2 Upper Río Piedras Drainage

The first order basin examined in the upper Río Piedras drainage is similar to the upper Río Chagrecito study area in size and slope angle. The drainage basin is developed off a major ridge, but lacks the steep head scarp found in the Chagrecito drainage. Four soils were described down the axis of this drainage basin. The relative thickness and horizonation of each soil profile are shown in Figure 3 and the morphological and compositional characteristics of the four soils examined are listed in Tables 3 and 4.

The Piedras-1 soil is described in a ridge crest position. It is a shallow soil developed over strongly fractured and weathered granite bedrock. The weathering is located primarily along joints and fractures. A weak A horizon overlies a transitional AB horizon which grades to a strong clay rich Bt horizon extending into the fractures. The bedrock fractures in the upper 40 cm of the profile are tilted in a downslope direction suggesting gradual creep downslope. The sand content of this soil is similar to that of the lowest soil in the Chagrecito drainage (Table 4).

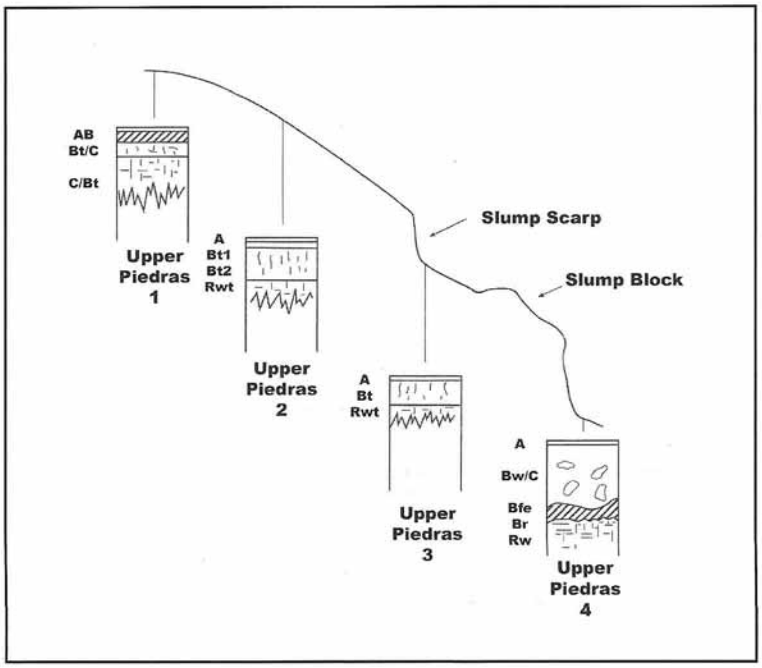

Figure 3. Diagrammatic representation of the Río Piedras soil profile locations

The Piedras-2 soil was from the steep backslope. It is the deepest soil of the four sampled in this drainage basin. Large fractures are found at the surface, which is covered in litter. This soil has a well developed A horizon and thick clay rich B horizons which overlie strongly weathered granite bedrock. A large root channel in the Bt horizon has clay and organic matter coatings suggesting that this is a conduit for water movement through the soil. The sand content of this soil is the highest of any soil in this drainage with equal amounts of silt and clay.

The Piedras-3 soil pit is located on the edge of a head scarp (45°) of a landslide. The soil has a thin weakly developed A horizon overlying 37 cm of yellow Bt on strongly weathered granite bedrock. Large fractures and joints in the bedrock are filled with clay and organic matter. The sand silt and clay contents are similar to that of the Piedras-1 soil.

The Piedras-4 soil is from a site at the base of the small drainage and consists of a large slump block. There is evidence of mixing of soil and unweathered regolith with weakly weathered and unweathered clasts juxtaposed. The soil regolith is loosely packed with numerous large pores and cracks with clay and organic matter staining along the edges. Parts of the soil profile have developed under reducing conditions, indicated by gley coloring and the formation of a weakly developed iron pan at the base of the reduced zone. This soil has a fine texture with 40 % sand, and equal amounts of silt and clay.

Table 3. Morphological description of the Piedras drainage soils.

Soil	Slope Position	Horizon	Color (moist)	Depth (cm)	Texture	Structure	Consistency (dry)
PD1	crest	litter		5-0			
		A1	10YR3/4	0-5	SiCl	3fcr	sh
		AB	10YR4/6	5-20	Cl	3msbk-3mcr	sh
		Bt/C	10YR5/8	20-40	Cl	M/3msbk	h
		C/Bt	10YR5/8	40-90	Cl	M/3msbk	h
PD-2	backslope (upper)	litter		5-0			
		A	10YR3/6	0-5	Sil	3mcr	sh
		Bt	10YR6/6	5-15	Cl	3msbk	sh
		Bt2	7.5YR6/4	15-60	Cl	3lsbk	sh
		Ct	7.5YR5/8	60-80+	SiCL	M	sh
PD-3	backslope (middle)	litter		3-0			
		A	10YR4/4	0-3	SiCL	3mcr	sh
		Bt1	10YR5/8	3-40	Cl	3msbk	sh
		Coxt		40-60	strongly weathered bedrock, fractures filled with clay, decrease with depth.		
PD-4	backslope (lower)	A	10YR4/3	0-3	SiCl	3fcr	s
		Bw/C	10YR4/6	3-100	Cl	3msbk	s
		Bfe	thin 3 cm iron pan at boundary with underlying gleyed horizon				
		Br	5BG4/7	103-120	Cl	M	NA
PD-5	terrace 25m above river	A	10YR3/3	0-15	SiL	3mcr	sh
		Bw/A	10YR4/6	15-27	SSiL	3msbk	sh
		2Ab	10YR3/6	27-45	SiCL	3msbk	sh
		2Btb	10YR5/6	45-80	CL	3msbk	sh
		2Coxrb	10YR6/4	80-120	SiCL	M	NA

The Piedras-3 soil pit is located on the edge of a head scarp (45°) of a landslide. The soil has a thin weakly developed A horizon overlying 37 cm of yellow Bt on strongly weathered granite bedrock. Large fractures and joints in the bedrock are filled with clay and organic matter. The sand silt and clay contents are similar to that of the Piedras-1 soil.

The Piedras-4 soil is from a site at the base of the small drainage and consists of a large slump block. There is evidence of mixing of soil and unweathered regolith with weakly weathered and unweathered clasts juxtaposed. The soil regolith is loosely packed with numerous large pores and cracks with clay and organic matter staining along the edges. Parts of the soil profile have developed under reducing conditions, indicated by gley coloring and the formation of a weakly developed iron pan at the base of the reduced zone. This soil has a fine texture with 40 % sand, and equal amounts of silt and clay.

Table 3. (cont.). Morphological description of the Piedras drainage soils.

Soil	Slope Position	Consistency (moist)	Roots	Pores	Comments
PD1	crest	ss,sp	2vf2f1m1l	3f large inter-granular spaces	
		ss,p	2vf3f2m1l	2f2m plus inter-granular spaces	
		s,p	1f1m	1m1l plus 4cm pipe	
		s,p	1f1m1l	1m root channel	
PD-2	backslope	so,sp	2vf2f2m	2vf2f	abundant worm burrowing
	(upper)	s,p	1vf1f1m1l	1f1m1l	3cm root channels
		s,p	1f1m1l	1vf1l	cracks from surface
		s,p	1m	1m	
PD-3	backslope	ss,sp	3vf3f2m1l	abundant inter-granular spaces	large factures with clay fims
	(middle)	s,p	1f2m2l	4 5-6 cm pipes	large fractures with clay Plus OM cutans
		ss,sp	2f1m1l	2f2m2l	several large pipes 4-5 cm diameter
PD-4	backslope	s,p	1f1m	2f2m2l	disturbed soil mass
	(lower)	s,p	2f2m	2m	
		so,po	2vf2f2m1l	2f	
PD-5	terrace	ss,sp	1vf2f1m1l	2vf2f	charcoal fragments
	25m	ss,sp	1vf1f1m	1vf1f	
	above	s,p	1f1m	1f1m	
	river	ss,sp	1m	1f	mottled plus concretions 2.5YR4/6

4.3 Clay Mineralogy

Six soil horizons were analysed to determine the dominant clay mineralogy of these soils. Three samples were from the Chagrecito-1 soil, the A, B1 and Cw horizons. All samples had the same dominant clay mineral, kaolinite or halloysite, the non-expanding halloysite. Three samples were taken from the Piedras-2 soil, A, B, and Cw horizons. These soils showed some variability in clay mineralogy but all were dominantly halloysite. The lowest horizon contained trace amounts of illite, smectite and interlayered illite/smectite.

Table 4. Particle size and bulk density data for the Chagrecito site soils.

Soil	Slope Position	Horizon	Bulk Density (g/cm3)	Sand %	Silt %	Clay %
Piedras-1	crest	litter				
		A1	1.2	45.4	28.5	26.1
		AB	1.42	45.4	24.6	29.8
		Bt/C	1.5	38.5	21.1	40.4
		C/Bt	1.42	41.1	23	35.8
Piedras-2	backslope	litter	1.33	66.1	24.3	9.5
	(upper)	A	1.37	55.1	21.9	22.9
		Bt	1.5	33.3	26.1	40.6
		Bt2	1.48	24.1	35.9	39.9
		Ct	1.46	49.8	32.1	18.1
Piedras-3	backslope	litter				
	(middle)	A	1.22	43.9	33.1	23
		Bt1	1.7	44.4	24.9	30.8
		Bt1	1.3	37	42.8	20.2
		Coxt	1.3	53.8	37.3	9
Piedras-4	backslope	A	2.05	43.9	33.1	23
	(lower)	Bw/C	1.37	44.4	24.9	30.8
		Bfe	N/A	N/A		
		Br	1.4	37	42.8	20.2
Piedras-5	Terrace	A		50.3	27.4	22.3
	25m above	Bw/A		55.7	22.2	22.1
	river	2Ab		50.8	25.9	23.2
		2Btb		36.1	20.7	43.2
		2Coxrb		31.8	21.5	46.7

5. DISCUSSION

5.1 Soil Development

In the absence of numerical ages for the landsurfaces in the study area, the degree of soil development can be used to determine the relative age of the regolith. Soil development in tropical regions is strongly controlled by the rate of weathering. The warm temperatures and abundant moisture mean that chemical weathering is rapid and is mostly occurring under oxidizing conditions. Characteristic changes in soil morphology and chemistry occur as a soil profile weathers over time. In general, a soil progressively loses the more mobile cations (*e.g.* Na, K, Ca) from exchange sites, which become dominated by Fe, Mg, Al, and silica. The particle size will decrease, and the soil texture will become more clay rich and there will be fewer unweathered clasts in the regolith. Soil horizonation will be more pronounced, especially with strong clay and red iron rich B horizons (Birkeland 1994). Generally tropical soils lack well developed A horizons as most the organic material is rapidly oxidized.

The soils can be ranked in order of increasing development based on the characteristics listed above – for the Chagrecito site: C-2 < C-3 < C-1 and for the Piedras site: P-4 = P-3 < P-1 < P-2 = P-5. Although the soils in the different drainage basins have similar morphology, there is insufficient data to determine if rates of soil development are similar on different lithologies in the two areas. In the Chagrecito drainage, the most strongly developed soil is at contact between the drainage basin and the main ridge. This soil has the greatest depth to saprolite, the strongest red color in the B, and the highest clay content of any soil. The other two soils in this basin are developed on transported regolith. They contain unweathered clasts and have a lower clay content. At the upper Piedras site, the most strongly developed soil is UP-2, on the upper part of the basin. The soil at the top of the basin is shallow, weakly developed, and is developing into weakly weathered bedrock, suggesting that pedogenesis is of short duration. The other two Piedras soils are both forming in transported regolith, have a significant proportion of unweathered clasts. The range of development of the soils in the study area is a reflection of different ages of site stability. This indicates that the landsurface in the drainage basins is diachronous, *i.e.* consists of individual soil elements of different age. The soil developed on a terrace surface in the upper Piedras location shows a similar degree of soil development as the most strongly developed soil on the hillslopes

5.2 Landscape Stability

The hillslopes in both drainages show evidence of extensive mass movement. At the Chagrecito site, the top of the drainage basin has a 2m head scarp exposing the most strongly developed soil in this drainage basin. Weathered saprolite is exposed at the base of the scarp in a linear erosion scar. This is the scar of a translational mass movement, which occurs at the boundary between the soil profile and saprolite. Vepraqskas *et al.* (1996) describe the physical changes that occur at the contact between the soil profile and saprolite that are reflected in the minimum K_{sat} determined in deeply weathered soil. They found that soil pores become blocked with clay and organic coatings, significantly reducing the saturated hydraulic conductivity at this point. Such physical changes may determine the failure plane for translational mass movements. Translational mass movements are slides that occur on shallow planar surfaces. The failure plane appears to be below the rooting depth of many of the trees and, therefore, trees may be moved while remaining in an upright position. The depositional part of the mass movement is reflected in the uneven topography and more weakly developed soils in the lower part of the basin. The two lowermost soils in this drainage contain numerous partially weathered clasts and weaker horizon development, which indicates less overall weathering and younger soils. Large trees are growing on the uneven topography, indicating that mass movement is predominantly translational and the trees are being episodically rafted downslope.

5.3 Pattern of Soil Variability

Although the soil pattern is determined by the frequency of disturbance, the mode of disturbance - translational flows - means that there is evidence of catenary relations as well within the drainage basins. The most stable soils were observed in upper slope positions, soils in the mid-slope and toe-slope positions were always forming in transported regolith. However, the lowermost soils in both drainages were strongly gleyed, indicating that reducing conditions exist in the soil for considerable periods of time. This was also the point where throughflow was observed exiting the hillslope regolith through pores, fractures, and root channels in the soil. In-situ soil profiles occupied an estimated 10-15% of the total area of the drainage basin in both study areas, with exposed saprolite incorporating another 10%, and the rest of the area consists of mass movement debris and disturbed soils.

5.4 Hydrologic Significance of Soil Properties

Soil properties influence the ease with which water enters and moves through the soil. The uppermost soil horizon for all soils is a weakly developed and thin A horizon. It contains little organic matter and the horizon has a high clay content. Large fractures were frequently found underneath the litter layer leading to the high infiltration rates measured in this part of the soil (Hendrickx *et al.,* 2005, this volume). Such features are not uncommon in soils with high clay contents, but the clay mineralogy of these soils is predominantly the non-expanding halloysite, kaolinite. The fractures may be tension cracks produced by the frequent mass movement occurring on these steep hillslopes. The fractures and uneven topography create preferred pathways for water movement from the surface. The mass movement deposit appears to have a lower bulk density and the regolith is loosely packed indicating increased macroporosity. The role of macropores in influencing streamflows in steep forested drainages has been described by Mozley (1982) and Casanova *et al.,* (2003). This work suggests that infiltration rates will be greater in the mass movement deposits than in soils higher on the hillslope. Another avenue for water entry into the soil is through the uneven topography created by mass movement and tree fall. Tree fall was observed frequently throughout the two drainage basins, but was more prevalent on the ridges - the more stable parts of the landscape. The process of tree fall produces a pit and mound topography, which persists in the landscape long after a tree, has disappeared. The upper soil horizons are removed and large fractures develop where tree roots have been torn out of the soil, creating preferred pathways into the subsoil. In temperate regions, enhanced leaching has been described as occurring in the pits indicating increased water movement through this part of the landscape (Schaetzl *et al.,* 1990).

In all soils of the upper Río Chagres basin study areas, preferred pathways for water movement were observed. Soil structure was mostly large angular blocky in the upper 50 cm. Along the faces of these soil peds, clay and organic staining was observed indicating water movement along these structural features. In each soil large former root channels, which were also coated with clay and organic staining, were observed.

6. CONCLUSIONS

The pattern of soil variability within two upper Río Chagres drainages reflects elements of both stability and instability. Translational mass movements, which raft weathered soil regolith downslope, are the dominant geomorphic process in both areas. The base of the translational mass movements appears to be the contact between the pedogenic soil profile and saprolite. Soils developed in transported regolith form the majority of the landsurface within the drainages, estimated at 60%. More stable soil profiles with higher clay contents and deeper weathering profiles are present in upper slope positions and form an estimated 10% of the total landsurface area. Catenary soil relations are observed in both drainages, with the stable soils in upper slope positions and gleyed soils occupying the lowermost parts of the drainages making up less than 5% of the area.

Soil properties strongly influence the entrance of water into the regolith and the stability of the regolith. The high clay content of even the less well-developed soil profile means that the soils will have high moisture retention values and the tree roots and disturbances due to mass movement mean that the soils should also have high macroporosity.

ACKNOWLEDGEMENTS

The 2002 fieldwork in the upper Río Chagres watershed was funded by the Tropical Regions Test Center (US Army Yuma Proving Ground), and we thank the organizers for their support. Other support was provided by the Universdad Technologica de Panama and New Mexico Institute of Technology.

REFERENCES

Birkeland PW, 1999, *Soils and Geomorphology*: Oxford Univ. Press, New York, NY.

Casanova, M, Messing, I, Abraham, J, 2000, Influence of aspect and slope gradient on hydraulic conductivity measured by tension infiltrometer: Hydrol. Proc., 14: 155-164.

Harden, CP and Scruggs, PD, 2003. Infiltration on mountain slopes: a comparison of three environments. Geomorph., 55, 5-24

Milne G, 1935, Some suggested units for classification and mapping, particularly for East African soils: Soil Res., 4: 183-198.

Mosley, MP, 1982, Subsurface flow velocities through selected forest soils, South Island, New Zealand: Jour. Hydrol., 55: 65-92.

Montgomery, DR and Dietrich, WE, 2002, Runoff generation in a steep, soil-mantled landscape: Water Resour. Res., 38: 1168, doi:10.1029/2001WR000822

Schaetzl, RJ, Burns, SF, Small, TW, Johnson, DL, 1990, Tree uprooting: Review of types and patterns of soil disturbance: Phys. Geogr., 11: 277-291.

Singer, MJ and Janitzky, PJ, eds., 1986, Field and Laboratory Procedures used in Soil Chronosequence Study: USGS Bull. 1648.

Tonkin, PJ, 1994, Principles of soil-landscape modelling and their application in the study of soil-landform relations within drainage basins. in Soil-landscape modelling in New Zealand: (TH Webb, ed.), Manaaki Whenua Press, Canterbury, NZ: 21-37.

USDA Soil Conservation Service, 1994, Keys to Soil Taxonomy: US Government Printing Office, Washington, DC.

USDA Soil Survey Staff, 1993, Soil Survey Manual: USDA Handbook No 18, US Government Printing Office, Washington, DC.

Vepraskas M.J., Guertal, W.R., Kleiss, H.J., Amoozegar, A., 1996, Porosity factors that control the hydraulic conductivity of soil-saprolite transitional zones: Soil Sci. Soc. Am. Jour., 60: 192-199.

Young, AW, 1988, A catena of soils on Bealey Spur, Canterbury, New Zealand. PhD Dissertation, Univ. Canterbury, NZ.