Chapter 8

HYDROLOGY OF HILLSLOPE SOILS IN THE UPPER RÍO CHAGRES WATERSHED, PANAMA

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Abstract: Soil hydrologcal processes determine how precipitation is partitioned into infiltration, runoff, evapotranspiration, and ground water recharge in the upper Río Chagres basin. The focus of this study is to investigate the soil hydrological processes by which precipitation excess on first order drainage basins enters the streams feeding the upper Río Chagres and its major tributary rivers. Infiltration rates, water retention curves, and water repellency of surface soils have been measured. These measurements together with the soil morphological observations by Harrison *et al.* (2005, Chapter 7) and hydrological observations by Calvo *et al.* (2005, Chapter 9) and Niedzialek and Ogden (2005, Chapter 10) are used to formulate a comprehensive conceptual model of runoff production in the upper Río Chagres watershed.

Key words: Panama, Panama Canal Watershed; upper Río Chagres basin; hillslope processes; soil hydrology

1. INTRODUCTION

The partition of precipitation into infiltration, runoff, evapotranspiration, and groundwater recharge in watersheds with steep slopes depends to a large extent on hillslope soil water dynamics (*e.g.,* Dingman, 2002; Anderson and Burt, 1990; Kirkby, 1978). These processes are not well understood, particularly in tropical rainforests. Bonell (1993) reviews the runoff generation process in forests, with an emphasis on tropical rainforests and states... "the varying runoff responses in tropical environments hinge on the delicate balance of rainfall intensity-soil hydraulic properties-topography".

R. S. Harmon (ed.), The Río Chagres, Panama, 113-138.

Calvo *et al.* (2005; Chapter 9) and Niedzialek and Ogden (2005; Chapter 10) present data that confirm Bonell's findings for the tropical upper Río Chagres basin. These investigators observed a disproportionably large volume of runoff during storms occurring immediately after the dry season and larger than normal runoff volumes during the wettest periods of the year. In addition, Niedzialek and Ogden (2005, Chapter 10) report that the discrete quasi-stable baseflows in the upper Río Chagres are not observed in the internal Río Piedras drainage which exhibits a more ephemeral behavior. The objective of this study was to identify the soil hydrological processes that cause the temporal variability in the rainfall-runoff relationships observed in the upper Río Chagres watershed.

2. SOIL HYDROLOGICAL PROCESSES THAT PRODUCE STREAM RESPONSES

This section presents an overview of the soil hydrological processes that may affect stream responses to precipitation events. Immediately after the start of a storm a large proportion of the precipitation contributes to 'surface storage'; later after infiltration of water into the soil, there is also soil 'moisture storage'. Two types of surface storage are recognized: retention and detention. Retention is storage held for a long period of time and depleted by evaporation; detention is short-term storage depleted by flow away from the storage location (Chow *et al.,* 1988). As the detention storages are filling up, flow away from them starts: surface runoff over the land surface, saturated flow through aquifers underlying the hillslope, and unsaturated flow through the soil near the land surface. The precipitation that becomes stream or channel flow reaches the stream either by falling directly into the channel or by surface runoff and/or subsurface flow.

Dingman (2002) classifies flow mechanisms that produce stream event responses with a focus on the soil hydrological processes. This classification has been slightly with the inclusion of water repellency in Table 1, which presents the soil hydrological processes contributing to stream flow during and after precipitation events on steep hillslopes.

Surface runoff or overland flow is caused either by saturation from above or by saturation from below. Runoff resulting from saturation from above has been first described by Horton (1933, 1945) and is also named 'Hortonian overland flow'. This type of runoff occurs when the rain intensity exceeds the infiltration capacity of the soil. Since the infiltration capacity of soils is in most cases higher than observed rainfall intensities, it is generally accepted that Hortonian overland flow occurs rarely on vegetated surfaces in humid regions (Chow *et al.,* 1988; Dingman, 2002). Saturation from above occurs mainly on impervious surfaces in urban areas, and on natural surfaces with thin soil layers and low infiltration capacity as in some semiarid and arid lands.

Table 1. Classification of soil hydrological processes contributing to stream flow in a first order drainage basin.

- I. Surface Runoff or Overland Flow
  - A. Saturation from Above (*i.e.,* Hortonian overland flow)
    - 1. Precipitation rate exceeds soil hydraulic conductivity
    - 2. Water repellent soil surface
  - B. Saturation from Below
    - 1. Decreasing soil hydraulic conductivity with depth
- II. Subsurface Flow
  - A. Saturated Subsurface Flow to Stream
    - 1. Flow from ground water mounds in shallow aquifer
      - a. Gradual mound development
      - b. Sudden mound development
    - 2. Flow from perched saturated zones
      - a. Darcian flow through soil matrix
      - b. Pipe and macropore flow
  - B. Unsaturated Flow
    - 1. Darcian flow through soil matrix
    - 2. Macropore flow

One important soil condition that can affect surface runoff is water repellency. It has been reported to occur worldwide: Australia, Canada, Colombia, Egypt, India, Italy, Japan, New Zealand, Poland, Portugal, South Africa, Spain, The Netherlands, and the USA (Jaramillo *et al.,* 2000). However, no reports were found on its occurrence in tropical lowland rainforests. In wettable 'normal' soils the initial infiltration rate is highest immediately after wetting and then decreases with time. In water repellent or hydrophobic soils the infiltration rate is lowest immediately after wetting and then increases with time (*e.g.,* Feng et al., 2002). The negligible to low infiltration rates after the start of a storm may cause water repellent soils to exhibit Hortonian behavior. Almost forty years ago, Krammes and DeBano (1965) argued that water repellency is a neglected factor in watershed management. In the late 1980s, Burch *et al.* (1987, 1989) report the occurrence of saturation from above due to water repellency in eucalypt forests. Yet, today water repellency is still not considered in most hydrology textbooks (*e.g.,* Chow *et al.,* 1988; Dingman, 2002; McCuen, 1998) and handbooks (*e.g.,* ASCE, 1996; Maidment, 1992). The effect of water repellency on surface runoff is most dramatically demonstrated after forest fires. Neary *et al.* (2003) summarize what is known about the effects of fire on watershed resources in the southwestern USA. Flood flows after wildfires often increase considerably due to factors such as combustion of vegetation and forest floor cover, development of water repellent layers in the soil, and accelerated development of post-fire thunderstorms. Increases in storm flows of 1.5 to 2,300 times the measured pre-fire flood peaks have been documented. The effect is especially severe in steep watersheds. Since the senior author observed water repellency during a previous visit in Panama, one important objective of this study was to systematically explore whether water repellency plays a role in the rainfall-runoff relations of the upper Río Chagres watershed.

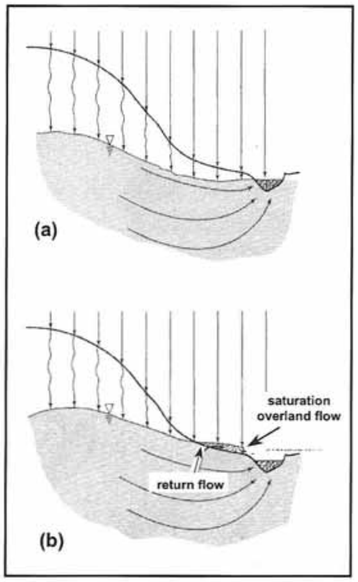

Figure 1. Saturation overland flow and sub-surface event flow due to near-stream ground water mounding. (a) Early stages of event; overland flow is absent and only regional ground water flow is (base flow) occurring. (b) Later, water table has risen to the surface in near-stream areas due to local and upslope recharge, infiltration ceases, and saturation overland flow results along with subsurface event flow. Return flow is the portion of saturation overland flow contributed by 'breakout' of ground water. Flow contributing to mounding results from both vertical recharge and downslope flow in the saturated zone (modified from Dingman, 2002; after Ward, 1984).

Runoff resulting from saturation from below occurs when the soil profile contains horizons with relatively low permeability or is underlain by a shallow ground water table. Once the soil becomes saturated, infiltration ceases and detention storage fills up resulting in surface runoff on hillslopes.

Surface runoff is the result of precipitation on saturated parts of the hillslope plus the contribution of ground water 'break-out' from upslope (Fig. 1).

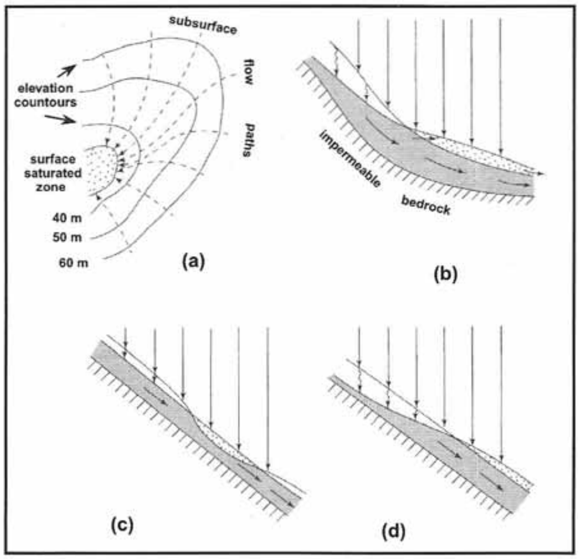

Figure 2. Situations in which saturation overland flow may arise on hillslopes outside of near-stream areas. (a) Plan view showing convergence of subsurface flow paths. (b) Cross-section showing downslope reduction in hydraulic gradient associated with slope break. (c) Cross-section showing local area of thin soil. (d) Cross-section showing formation of perched saturated zone above low-conductivity layer with constant slope and soil thickness. (modified from Dingman, 2002; after Ward, 1984).

Field studies (Dunne and Black, 1970; Dunne, 1978; Ward, 1984) and modelling (Freeze 1972, 1974) have shown that this mechanism is important in humid areas. Although saturation from below will most likely occur in drainage basins with concave hillslope profiles and in flat valleys, it is not restricted to near-stream areas. Ward (1984) describes four different scenarios where surface runoff may arise on hillslopes away from the streams (Fig. 2): (a) Convergence of water flow paths into slope concavities; (b) Downslope reduction in hydraulic gradient associated with slope break; (c) Subsurface flow conducted through thin soil layers; and (d) Zones of perched ground water 'break-out' at soil surface. Within a watershed the extent of areas saturated from below varies greatly with time. In many regions this temporal variability of overall watershed wetness causes a large temporal variability in storm runoff (Dingman, 2002).

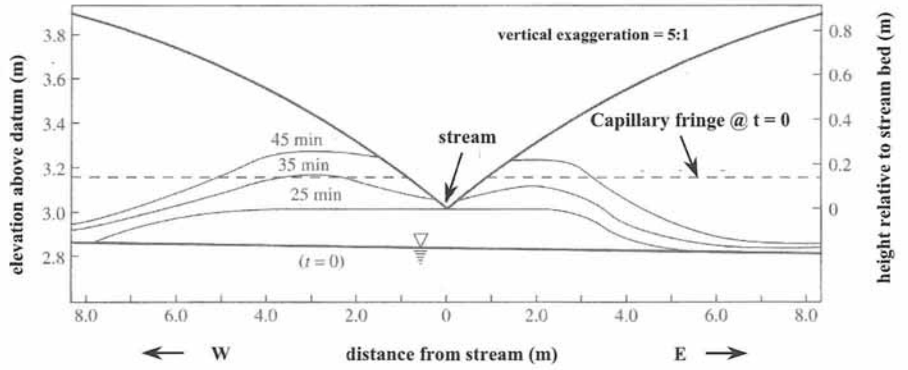

Figure 3. Quick response of a near-stream water table due to pressurization of the capillary fringe during a simulated rain of 2 cm/hr in a sandy soil. Lines show position of ground water table at successive times after onset of the rain (modified from Dingman, 2002; after Abdul and Gillham, 1989).

Saturated subsurface flow is generally considered the source of most streamflow between precipitation events, *i.e.* the base flow. It is recognized that the travel times of regional ground water flows are so large that the short-term pulses of precipitation are damped out before reaching the streams. However, tracer studies have revealed that under certain conditions ground water can be a significant part of short-term stream response to precipitation events (*e.g.,* Sklash and Farvolden, 1979; Space *et al.,* 1991).

Saturated subsurface flow to streams can occur due to local gradual ground water mound development near streams as well as from flow through perched saturated zones. Ground water recharge during rainfall events can produce a mound that increases the hydraulic gradient toward the stream and so produces a prompt contribution to streamflow. A special case is where sudden pressurization of the capillary fringe and unsaturated zone above shallow ground water tables causes an almost instantaneous formation of sudden ground water mounds (Abdul and Gillham, 1984, 1989; Jayatilaka *et al.,* 1996). The streamflow contribution generated by this mechanism may greatly exceed the amount of water needed to pressurize the capillary fringe and unsaturated zone from negative to positive pressure (Fig. 3).

Unsaturated subsurface flow can never be a direct source of water to a stream. Soil water pressures in unsaturated flow are negative, whereas water pressures in a stream are positive. Only when soil water pressures build up in a soil to slightly positive pressures, can water leave the unsaturated zone and enter the shallow aquifer or move through a seepage face into the stream.

During wetting events infiltration on hillslopes is nearly vertical for most soils, while shallow unsaturated flow tends to become parallel with the slope during drying events (Jackson, 1992). This phenomenon typically leads to two distinct flow regimes on steep hillslopes: one during wet episodes and another during dry periods. During wet periods, infiltrating water can cause a perched saturated zone that feeds the stream on hill slopes that consist of a thin permeable soil layer overlying a relatively impermeable layer, (Fig. 4).

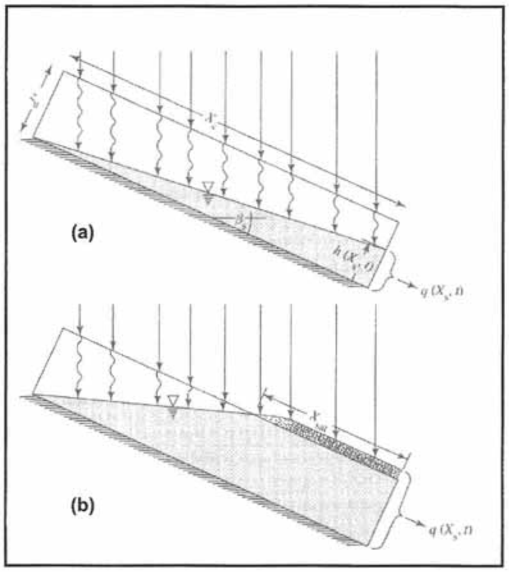

Figure 4. Formation of a perched saturated zone on a hill slope in which a soil horizon with relatively high hydraulic conductivity overlays a soil horizon with relatively low hydraulic conductivity. (a) Subsurface storm flow from basal saturated zone at slope base. (b) Sloping slab with 'breakout' water near the stream, producing saturation overland flow with subsurface storm flow (from Dingman, 2002).

The response time of this runoff process on steep slopes can be evaluated using simple conceptualisations and is on the order of hours (Dingman, 2002). During dry periods on steep hillslopes, the near-surface soil water equipotential lines become normal to the slope which causes unsaturated water flow parallel to the slope and accumulation in the 'toe' (Fig. 5). Since unsaturated flow parallel to a hillslope is a slow process, this flow will not contribute to event response but it can be a main source of base flow during the dry season (*e.g.,* Anderson and Burt, 1977; Hewlett and Hibbert, 1963; Nutter, 1975; Weyman, 1970).

Hewlett and Hibbert (1963) demonstrated the potential for base flow maintenance by unsaturated flow from uplands with an illustrative experiment. They saturated a confined column soil (1m x 1m x 15m) of homogeneous sandy-clay-loam, covered it to prevent evaporation, tilted the soil column at a 40° slope, and its discharge was measured at the slope base. Since unsaturated flow parallel to a hillslope is a slow process, this flow will not contribute to event response, but it can be a main source of base flow during the dry season (*e.g.,* Anderson and Burt, 1977; Hewlett and Hibbert, 1963; Nutter, 1975; Weyman, 1970). As expected, the discharge rates declined very rapidly during the first five days from *c.* 620 to *c.* 50 liters per day. However, drainage persisted until the experiment was terminated on day 145. After three months (*i.e.,* the approximate length of the dry season in the upper Río Chagres watershed), the discharge was still about 1 liter/day.

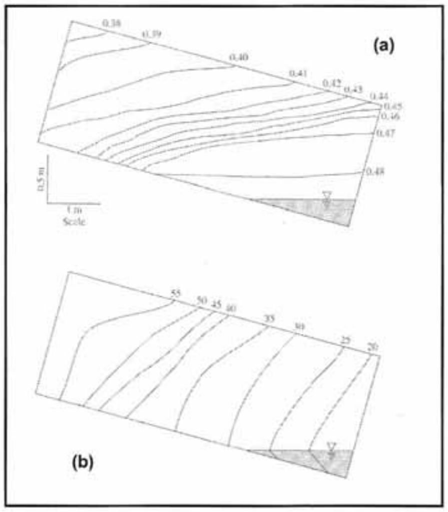

Figure 5. (a) Water content and (b) hydraulic head distribution in a sloping slab after 749 hours of drainage. The slope is 15°. The equal head lines are perpendicular to the soil surface indicating slope parallel flow, which is typical for draining conditions between storm events. Also, note the saturated wedge at the toe slope (from Dingman, 2002; after Nutter, 1975).

Macropores and pipes are produced by roots, soil fauna, or desiccation cracking. Their sizes can vary from a few millimetres to more than 100 mm. Stresky (1991) observed in a New Hampshire forest that macropore networks were generally oriented downslope and were interconnected over distances of at least tens of meters. Therefore, these features provide pathways for water to bypass the soil matrix and to move downslope to the shallow aquifer at velocities of several millimetres per second (*e.g,* Beven and German, 1982; Hendrickx and Walker, 1997; Mosley 1979, 1982). In many cases, it is unclear whether the soil matrix surrounding the macropores was saturated or unsaturated, but for water to enter larger macropores and pipes soil water pressures need to become slightly positive at the point of entrance. Once water is inside the macropore network, it can be transported downslope through otherwise unsaturated soils. Many studies indicate that the importance of macropore flow increases with the amount of precipitation in an event (Dingman, 2002). German (1986) analysed drainage responses to storms observed during a 7-year period in the Coshocton monolith lysimeters (Northeast Experimental Watershed, USDA-ARS, Coshocton, Ohio). Rains of only 10 mm/day caused a drainage response at 2.4 m depth on the same day as precipitation when volumetric water content in the upper meter of the undisturbed soil profile exceeded a threshold value of 0.3 m^3/m^3, whereas at soil water contents below this threshold value storms greater than 50 mm per day were found not to cause any drainage flow. This demonstrates that macropore flow also increases with soil water.

3. METHODS AND MATERIALS

Most of the data for this study have been obtained during the upper Río Chagres field campaign of 4-16 March 2002. The field work was conducted in two small, narrow, and steep first order drainage basins with similar morphologies: at a site in the upper Río Chagrecito drainage (approximate coordinates: 9°22′ N latitude, 79°19′ E longitude) and the upper Río Piedras drainage (approximate coordinates: 9°18′ N latitude, 79°20′ E longitude). Harrison *et al.* (2005, Chapter 7) describe the methods for soil morphology and geomorphological observations in the field. In addition, to these qualitative observations we have also measured infiltration rates and water repellency in the field.

Tension disc infiltrometers (*e.g.,* Clothier and Scotter, 2002) were taken to the field. However, these instruments of choice could not be employed for the following reasons: (1) Even during the dry season the upper Río Chagres basin receives frequent showers wetting the river sand beds. Since moist sands cannot be sieved, it was difficult to obtain the supply of fine sand needed to install the infiltrometer on the soil; (2) Especially in the upper soil layers roots tend to damage the sensitive membrane; (3) Each infiltration measurement in the fine textured soils would have taken a long time, thus limiting the total number of measurements possible. For these reasons, the crude method of 'test pits' (USBR, 1984) had to be used. A small test pit (0.3x0.3 m with depth 0.2 m) was dug out in the soil horizon of interest. After filling it with water to a depth of about 0.15 m, the fall of the water level in time, *i.e.* the infiltration rate, was monitored by reading a ruler placed in the bottom of the pit (Fig. 6). When the water level had fallen by about 0.05 m, the water level was brought back to its original level. This method definitively overestimates the infiltration rates but it yields information on the relative infiltration rates of representative soil horizons. Measurements were made in four soil pits at the Piedras drainage site (RP-1, RP-2, RP-3, and RP-4) and in two soil pits at the Chagrecito drainage site (C-1 and C-2). A full description of these soil profiles is given by Harrison *et al.*, 2005, Chapter 7).

Figure 6. Measurement of upper limit of infiltration rates in small test pits.

Soil water repellency in the field and in the laboratory is determined with the empirical 'Water Drop Penetration Time' (WDPT) test described by several investigators (*e.g.,* Dekker and Jungerius, 1990; King, 1981; Krammes and DeBano, 1965; Letey *et al.*, 1975). Three drops of water from a standard medicine dropper are placed on the smoothed surface of a soil sample, and the time that elapses before the drops are absorbed is determined. Using the WDPT test on dried samples in the laboratory gives the persistence of the potential water repellency while its use on field-moist samples yields the actual water repellency (Dekker and Ritsema, 1994). Different classification systems for water repellency are used (King, 1981; Dekker, 1998). A soil is considered wettable if the penetration time is less than 5-10 sec; slightly water repellent if the penetration time is 10-60; water repellent if the penetration time is 60-90 sec; and strongly water repellent at longer penetration times.

In the field, 1-m long transects were selected close to the soil profile pits described by Harrison *et al.* (2005, this volume). Along each transect, the litter was carefully removed to expose the surface soil. Next, 20 soil rings (diameter = 0.05 m; height = 0.05 m) were inserted side by side. Then, the WDPT test was administered on the soil surface within each of the rings. The soil sample within each ring was put in a plastic bag for transport to the hydrology laboratory at New Mexico Tech. There, the soil water content was measured. In addition, the WDPT test was repeated after air drying the samples for several weeks. Soil ring samples (diameter = 0.05 m; height = 0.05 m) were collected in six of the representative soil horizons described by Harrison *et al.* (2005, this volume), for determination of the soil water retention curve at New Mexico Tech using the hanging water column technique (Dane and Hopmans, 2002).

4. RESULTS AND DISCUSSION

This section discusses what has been learned about the soil hydrological processes that contribute to stream flow response in the upper Río Chagres basin. The discussion is structured along the soil hydrological processes presented in Table 1, based upon both field and laboratory measurements as well as the field observations described by Harrison *et al.* (2005, this volume).

4.1 Surface and Soil Moisture Storage

The shapes of the first order drainage basins in the upper Chagrecito and upper Río Piedras drainages are similar to those shown in Figures 2a and 2b. Slope angles in the two basins vary from approximately 55° at the head of the basin to approximately 20° at the toe. Harrison *et al.* (2005, Chapter 7) observed extensive mass movement in both drainages that generated an uneven topography, especially in the lower slope areas. They also observed frequent tree fall (Fig. 7), especially on the higher, more stable, parts of the drainages.

After a tree has fallen a pit and mound topography will persist in the landscape long after the tree has disappeared. Despite the steep slopes the uneven topography creates many local depressions that provide a considerable volume for surface storage of precipitation and run-on water from upslope. Some of the detained water will evaporate, but most will infiltrate into the soil to increase soil moisture storage and, therefore, the propensity for macropore flow. Ponding of surface water in small depressions will result in small positive water pressures that also allow water to enter the macropore and pipe system. It will be hypothesized below how the combination of these local depressions with water repellent soil surfaces after the dry season could create a system of bypass flow that allows quick downward transport of storm water into the pipe network through an unsaturated soil matrix.

Figure 7. Fallen tree - a common occurrence throughout the upper Río Chagres basin.

4.2 Surface Runoff Caused by Saturation from Above

Saturation from above occurs when the precipitation intensity exceeds the infiltration capacity of the soil. The upper limits of the infiltration rates measured in the different soil profiles are presented in Table 2. The infiltration rates measured near the soil surface appear to be relatively high given the amount of clay in the soil (Harrison *et al.*, 2005, this volume). However, the blocky soil structure and the large number of cracks and macropores close to the soil surface often result in high infiltration rates in tropical forest soils (*e.g.,* Bonell *et al.*, 1981). These high infiltration rates will make the occurrence of Hortonian flow most unlikely as long as the soil surface is wettable, i.e. not water repellent.

Water repellent soil surfaces have a much lower infiltration rate than the same soil surface under wettable conditions. Since water repellency is enhanced when the soil becomes dry, it is expected that the effect of water repellency on runoff is the strongest immediately after the dry season. The degree of water repellency has been measured in the field and in the laboratory. The results are presented in Tables 3 and 4.

Table 2. Upper limits of infiltration rates in selected profiles of the upper Río Piedras (RP) and upper Río Chagrecito (C) drainages. See Harrison *et al.* (2005, Chapter 7) for full soil profile descriptions.

Profile	**Depth (cm)**	**Horizon Description**	**Upper Limit Infiltration Rate (cm/day)**
RP-1	10	A/B	5,760
	40	C/Bt Clay in fractures	26
	80	C/Bt Clay in fractures	19
RP-2	40	Bt2	9
	80	Cox/t Saprolite with clay in fractures	55
RP-3	40	Cox/t Saprolite with clay in fractures	180
	80	Cox/t Saprolite with clay in fractures	160
RP-4	10	Bw/C Disturbed horizon	14,400
C-1	10	Bt	60
	120	Saprolite	180
	300	Saprolite	85
C-2	50	Bt	85

The 'Water Drop Penetration Test' (WDPT) measurements show that water repellency does occur in the upper Río Chagres watershed, but the areal extent of water repellency is not at all clear. At the Chagrecito-1 site, four of the laboratory dried samples are water repellent (Table 3), two samples are slightly water repellent at Chagrecito-2, and at Chagrecito-3 no sample shows any degree of water repellency. The field measurements on 7 March 2002 at the Chagrecito-1 site resulted in 17 out of 20 samples water repellent or strongly water repellent. However, on 8 March 2002, the field measurements at the Chagrecito-2 and Chagrecito-3 sites documented no water repellency. This negative result was probably caused by the moist soil conditions, as measured gravimetric water contents ranged from 0.54 to 1.77 kg/kg following heavy showers which occurred during the previous night. At the Piedras-1 site, 13 field samples exhibit strong water repellency and the other samples some degree of water repellency, At the Piedras-2 site, 11 field samples were water repellent, whereas at the Piedras-3 only a single field sample was slightly water repellent. By contrast, samples from the Piedras-1 and Piedras -2 sites were much less water repellent when measured under laboratory conditions.

Table 3. Gravimetric field soil water content and results of Water Drop Penetration Test (WDTP) on soil surface samples from the Chagrecito drainage. Wettable = 0-10 sec, slightly water repellent = 10-60 sec, water repellent = 0-90 sec, strongly water repellent = >90 sec. WDPT of field is average of three drops; WDPT lab is average of five drops.

Site	**Chagrecito - 1**			**Chagrecito - 2**			**Chagrecito - 3**		
-----------	Field	Field	Lab	Field	Field	Lab	Field	Field	Lab
Distance (cm)	wc (g/g)	WD PT (sec)	WD PT (sec)	wc (g/g)	WD PT (sec)	WD PT (sec)	wc (g/g)	WD PT (sec)	WD PT (sec)
5	0.55	8	1	1.08	1	1	0.72	1	1
10	0.58	58	1	1.29	2	4	0.80	2	1
15	0.54	12	3	1.21	6	1	0.85	1	1
20	0.62	21	3	1.36	4	1	0.76	1	2
25	0.59	2	75	1.41	3	6	0.86	1	2
30	0.57	20	95	1.41	3	10	0.65	1	1
35	0.61	203	13	1.33	2	14	0.73	1	1
40	0.65	27	3	1.27	3	2	0.67	1	0
45	0.65	3	8	1.30	1	1	0.70	1	1
50	0.64	20	1	1.28	1	7	0.80	1	1
55	0.64	151	1	1.28	2	2	0.82	1	1
60	0.64	236	2	1.42	2	4	0.83	1	1
65	0.62	92	4	1.49	1	1	0.75	1	1
70	0.61	161	1	1.53	4	2	0.72	1	1
75	0.64	46	10	1.73	2	6	0.59	1	1
80	0.63	93	1	1.77	2	3	0.89	1	1
85	0.63	286	6	1.18	2	5	0.65	1	1
90	0.61	186	2	1.49	1	2	0.63	1	2
95	0.63	34	2	1.29	2	3	0.64	1	1
100	0.64	26	1	1.32	2	1	0.65	1	1
Average	0.61	84	12	1.37	3	4	0.73	1	1

The dynamic behavior of soil water repellency is not yet understood. In general, the degree of soil water repellency decreases with soil moisture content. It also has been reported that the degree of water repellency changes with different drying temperatures. For example, Dekker (1998) found for 4 out of 7 sandy soil sites in The Netherlands that water repellency was greater after drying at 65°C relative to 25°C, whereas it decreased for 2 others, and remained unchanged for one. Doerr *et al.* (2002) found that an increase in relative humidity from typical ambient laboratory conditions, *i.e.,* 40-50% relative humidity, to 98% for a time period of less than one day increased the degree of water repellency strongly. This finding may explain the large differences observed between field and laboratory WDPT values observed at Chagrecito-1 site and the Piedras-1 and Piedras-2 sites. The much lower degree of water repellency measured in the laboratory compared to that determined in the field, may have been caused by the low humidity in arid New Mexico versus the high humidity in the field in Panama.

The field and laboratory measurements, together with observations of water repellency made by the senior author during the dry season of 2001, leave no doubt that water repellency does occur in the in the upper Río Piedras watershed. It is hypothesized that a combination of dry soil surfaces and high relative humidity create patches of severe water repellency just before the first storms after the dry season. Instead of precipitation filling up the dry soil profiles – as is assumed by many hydrological models – it will run off into the many depressions created by the uneven topography of the drainages. At the lowest points in these depressions, a slightly positive water pressure will develop that allows the runoff water to enter the system of macropores and pipes. As soon as the water starts flowing in this natural drainage system, it can bypass the large dry soil mass on the hillslope and move downward at a high velocity. At the toe of the hillslope, this water contributes to the shallow aquifer feeding the stream. After the surface soils have been wetted at the start of the rainy season, water repellency probably does not any longer affect the relation between precipitation and runoff.

4.3 Surface Runoff Caused by Saturation from Below

Saturation from below occurs when the soil profile contains less permeable layers or is underlain by a shallow ground water table. Our infiltration measurements (Table 2) and the observations by Harrison *et al.* (2005, Chapter 7) show that the occurrence of a less permeable B horizon is a typical feature of the hillslope soils in the watershed. At the Piedras site, the upper limits of the infiltration rates in the B horizon are two to three orders of magnitude less than those of the overlying soil horizons. Therefore, it is expected that saturation from below is a common feature during the wet season when soil water content is high and precipitation frequent (Fig. 2d). The severe decrease of saturated hydraulic conductivity with depth seems to be not uncommon in tropical watersheds, having been reported in tropical Australia (Bonell *et al.,* 1981) and in the Amazon (Elsenbeer *et al.,* 1992). Saturation from below due to a shallow ground water table may occur during wet periods at the toe slope (Fig. 1b) or where the ground water table breaks out the slope due to a reduction in hydraulic gradient associated with slope break or local areas of thin soil (Fig. 2b, c).

Table 4. Gravimetric field soil water content and results of the 'Water Drop Penetration Test' on soil surface samples from the Piedras drainage. Wettable 0-10 s, slightly water repellent 10-60 s, water repellent 60-90 s, strongly water repellent >90 s. WDPT of field is average of three drops; WDPT lab is average of five drops.

Site	Upper Río Piedras-1			Upper Río Piedras-2			Upper Río Piedras-3		
----------	Field	Field	Lab	Field	Field	Lab	Field	Field	Lab
Distance (cm)	wc (g/g)	WD PT (sec)	WD PT (sec)	wc (g/g)	WD PT (sec)	WD PT (sec)	wc (g/g)	WD PT (sec)	WD PT (sec)
5	0.28	54	43	0.25	4	2	0.31	1	1
10	0.27	334	101	0.24	29	2	0.30	2	1
15	0.26	337	94	0.23	27	1	0.32	2	1
20	0.33	55	92	0.21	64	20	0.32	1	1
25	0.30	11	23	0.23	93	12	0.32	2	2
30	0.26	31	14	0.22	103	6	0.32	3	2
35	0.29	59	16	0.23	121	2	0.30	8	1
40	0.28	33	62	0.25	20	12	0.32	2	1
45	0.37	307	7	0.22	21	10	0.30	8	1
50	0.30	513	10	0.22	99	2	0.32	2	1
55	0.26	767	150	0.22	21	2	0.31	2	1
60	0.28	1127	87	0.30	6	1	0.30	2	1
65	0.30	775	71	0.29	5	1	0.30	2	1
70	0.29	351	32	0.29	2	1	0.29	12	1
75	0.29	632	96	0.29	3	1	0.27	7	1
80	0.31	428	81	0.27	3	2	0.28	5	1
85	0.30	470	24	0.29	2	22	0.28	3	1
90	0.29	232	47	0.31	19	3	0.27	3	1
95	0.30	78	67	0.28	2	2	0.30	3	1
100	0.33	251	38	0.26	2	1	0.29	2	1
Average	0.30	342	58	0.26	32	5	0.30	4	1

4.4 Saturated Subsurface Flow

The presence of (almost) permanently saturated flow in soil profiles is marked by reduced conditions that lead to distinctive blue-greyish gley mottles. Harrison *et al.* (2005, Chapter 7) have observed such gley mottles in the soil profiles at the toe slopes of the drainages. No gley mottles have been observed in any of the soil profiles on either the hill crests or backslopes, which indicates that saturated subsurface flow is not a permanent condition on the hillslope. Although saturated through flow as a result of perched water tables almost certainly will occur during wet periosds, such flow events will have a short duration. Most likely, the network of macropores and pipes on the hillslope will act as a subsurface drainage system that quickly evacuates large volumes of water to the shallow aquifer under the toe slope adjacent to the stream.

The inflow of water into the shallow aquifer will lead to the build up of a groundwater mound and an increased discharge into the stream (Figs. 1b, 2b, 4b). The steep soil water retention curves presented in Figure 8 indicate that a relatively small amount of water can cause a large sudden change in soil water pressure along the hillslope resulting in sudden ground water mounds (Fig. 3). For example, under moist conditions (*i.e.,* soil water pressure about 250 cm), the soil in the B horizon of Chagrecito-1 at depth 120 cm needs only 2-3 cm of infiltration to raise the ground water level 250 cm.

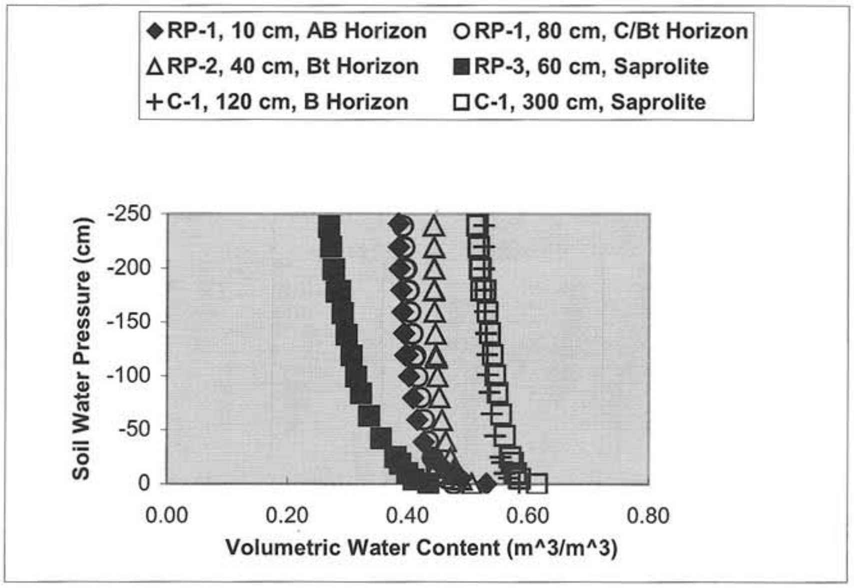

Figure 8. Soil water retention curves from different soil horizons in the Chagrecito and Piedras drainages.

Saturated shallow subsurface flows appear to be periodic in nature with the exception of the waters seeping from toe slopes. However, deep saturated subsurface flows in the aquifers underlying the hillslopes are a permanent feature of the upper Río Chagres basin, as is observed in the 10 to 20 m deep wells used by the local population for drinking water. These deep ground water supplies are expected to become important for the future development of water resources in the watershed especially during episodic periods with scarce water supplies. Since little is know about the hydrogeology of the watershed the investigation of aquifers, recharge, and the ground water volumes available for exploitation should have a high priority.

4.5 Unsaturated Subsurface Flow

Three types of unsaturated subsurface flow are recognized along the hill slopes in the two drainages: (i) a vertical downward flow from the soil surface into the soil matrix after the start of and during precipitation events, (ii) a continuous vertical downward flow leaving the less permeable B horizons and entering into weathered and unweathered bedrock, and (iii) a lateral downhill flow component parallel to the soil surface after precipitation has ceased.

As has been discussed above, the unsaturated downward flow from the soil surface will be overtaken by saturated flow during storm events due to saturation from below at the interface of the A and B horizons, which is caused by the lesser permeability of the Bt horizons. This phenomenon is well recognized in surface water hydrology. However, it also should be acknowledged that the less permeable B horizon is not completely impermeable and, therefore, a substantial volume of water will pass through it to become ground water recharge. The volume of ground water recharge in the upper Río Chagres watershed is a major unknown; quantification of this component of the water balance is critical for the development of water resources management strategies during drought periods.

It is hypothesized that the lateral downhill unsaturated flow component is critical to maintain base flow during the dry season and in between major precipitation events. Support for this idea is found in the large water holding capacity of the hillslope soils, which varies from about 60 to 45 vol. % (Fig. 8). These water holding volumes are similar to those observed in the soils for the lateral unsaturated flow experiments by Hewitt and Hilbert (1963) described in Section 2. Further evidence is provided by the discharge measurements made for one of the springs exiting from the toe slope of the Chagrecito site at the end of the 2002 dry season. Before the heavy rain during the night of 7-8 March 2002, the spring discharge measured 5.5 liters/min; on the morning after the rain it measured 6.5 litres/min. The relatively small effect of the precipitation on spring discharge during the dry season indicates that the springs are mainly fed by unsaturated flow (Fig. 5), which is a slow process. Thus, contrary to many other watersheds where the source of base flow is the regional aquifer, baseflow in the upper Río Chagres basin between storm events and during the dry season is mainly fed by downward- seeping unsaturated flow. As shown by the experiments of Hewlitt and Hibbert (1963,) this kind of flow can maintain considerable discharge where precipitation events occur on a regular basis. At the

Chagrecito site, where drainage covers about 1 hectare; 2 to 3 springs were estimated to yield a total discharge of about 15 litres/min from the drainage. Extrapolating this discharge to the entire approximately 400 km^2 of the upper Río Chagres watershed yields a discharge of 600 m^3/min or 10 m^3/sec. The latter discharge is quite similar and certainly at the same order of magnitude as the estimate presented by Niedzialek and Ogden (2005, this volume) during the dry season of 2001.

4.6 Macropores and Pipes

An abundance of macropores, cracks, and pipes was observed in each of the eight soil profiles described by Harrison *et al.* (2005, this volume). The diameter of the pipes could be up to about 10 cm (Fig. 9), a dimension similar to subsurface drains used in agriculture.

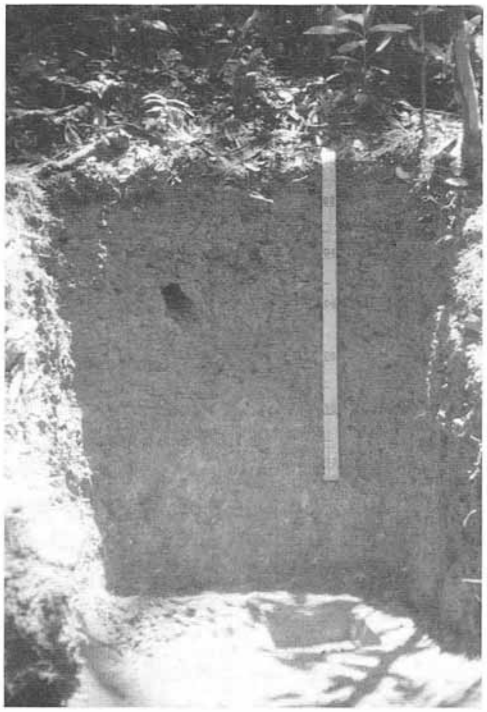

Figure 9. A typical soil pipe with diameter 12 cm in soil profile RP-2.

For water to enter the pipes and macropores a positive water pressure is required. Two mechanisms are recognized for a positive water pressure to develop along the hill slope. The first is the situation where saturation from below leads to saturated conditions, *i.e.* a positive water pressure, around soil pipes. This mechanism could develop very quickly, especially in moist soil where only a small amount of infiltration is needed to make soil water pressures positive due to the steep water retention curves measured in the hill slope soils (Fig. 8). The second mechanism would operate where water accumulation in small soil surface depressions leads to ponding and positive water pressures. This mechanism will convey runoff water into the soil pipe network even when the hill slope soils are unsaturated. Critical factors for the latter mechanism are the uneven topography and the occurrence of water repellency after dry periods.

Co-author Rojas, a ranger in the Parque Nacional Chagres (Chagres National Park), has often observed that the pipes release jets of water during heavy precipitation events. This not only indicates that some pipes carry water under considerable pressure at full flow condition, but also that a water drop may travel downhill through a sequence of surface runoff and pipe flowpaths. The exfiltration of water from pipes on tropical hill slopes has also been reported by Bonell *et al.* (1984) and Elsenbeer and Cassel (1990).

5. CONCEPTUAL RUNOFF PRODUCTION MODEL

Calvo *et al.* (2005, Chapter 9) and Niedzialek and Ogden (2005, Chapter 10) have analysed preciptation-runoff relations in the upper Río Chagres basin and found anomalously high runoff production at the start of the wet season and discrete quasi-stable baseflows during the hydrologic year. The soil hydrology observations discussed here form the basis for the formulation of a hypothetical, comprehensive conceptual model for runoff production that explains the apparently anomalous precipitation-runoff situation observed in the upper Río Chagres watershed.

The key factors that affect runoff production along the tropical hill slopes of the upper Río Chagres watershed are: steep gradients, extensive macropore and pipe networks, soils with high water retention, B horizons with relatively low permeability overlain by A/B horizons with relatively high infiltration capacity, the occurrence of water repellency and cracks when soil surface dries out, uneven topography with many small surface depressions, and high precipitation events.

The model discussion begins at the start of the wet season when the soil surfaces are relatively dry and soil cracks have developed. At this time, the water content of the upper layers of the soil profile is relatively low. The relatively few water content measurements made suring this study indicate that at least 20 vol. % pore space is available for soil water storage. The measurements presented in Tables 3 and 4 indicate the occurrence of a state of water repellency after the dry season.

Calvo *et al.* (2005, this volume) and Niedzialek and Ogden (2005, this volume) report anomalously high runoff volumes during the first storms of the subsequent wet season. Obviously, bypass flow carries a large volume of precipitation quickly downhill without wetting the soil matrix. Since about 20 vol. % of the soil is available for water storage, saturation from below has to be excluded as a possible runoff mecihanism. Overland flow is also unlikely given the relatively high infiltration rate of the soil surface and the uneven topography. The only other quick response flow pathway is the macropore and pipe network. However, for water to enter this network a positive water pressure is needed.

Therefore, it is hypothesized that the uneven topography caused by mass movement along the unstable slope and tree fall results in a large number of small surface depressions which provide the necessary source of water. These surface depressions accumulate water relatively quickly as rains begin due to the water repellency that prevents infiltration into the soil surface and enhances the runon towards the lowest points in the depressions. Here, almost immediately a positive water pressure develops that allows the runon water to enter the pipe network. Once the water is in the pipes it moves rapidly downhill. Niedzialek and Ogden (2005, Chapter 10) argue that dry season soil cracks would lead to increased soil storage [and reduced runoff, *sic*]. This is true for cracks without an outlet. However, along the hill slopes in the two drainages, the cracks would fill up with water swiftly and create additional water sources with positive water pressures that feed into the pipe network. Thus, the quick filling of small depressions and cracks due to a water repellent soil surface allows the development of water sources with positive water pressures that feed immediately into the downhill pipe network. It is this process that is envisaged to cause the anomalously high runoff volumes observed for the upper Río Chagres basin at the start of the wet season.

Once the wet season has started, the moist soil surface causes the water repellency disappear and infiltration into the soil matrix starts to fill the soil water storage reservoir. In addition, most soil cracks will have disappeared due to swelling of the clay minerals upon wetting. As a consequence, the volume of runon water towards the lowest points in the small surface depressions will decrease. This, in turn, leads to lower positive water pressures and less water entering the downhill pipe network. Therefore, it is expected that the amount of runoff for a given storm will decrease as compared to the runoff observed at the start of the wet season. Indeed, Calvo *et al.* (2005, Chapter 9) report a sharp decrease in the 'Curve Number', *i.e.* a measure of the runoff volume, immediately after the first storms of the wet season. Their analysis supports our hypothesis.

During the wet season, two critical sequential threshold values of soil moisture are recognized: one where the macropores and pipes become active due to localized saturation inside the soil profile around the pipes and another where saturation from below reaches the soil surface and starts to enhance surface runoff. The steep water retention curves of the soils along the hill slopes (Fig. 8) create a situation where a small amount of water added to a moist soil can generate the rapid development of a positive water pressure around macropores and pipes. This will cause water to enter the pipe network and leads to an increased runoff volume. The soil moisture content at which this process starts is the 'critical soil moisture threshold for macropore flow'. For example, German (1986) found a threshold value of 30 vol. % water which is well below saturation.

Finally, during the peak of the rainy season and during prolonged storms soil moisture conditions will reach saturation throughout the soil profile at the 'critical soil moisture threshold for saturation from below'. Now, not only the pipe network will be conveying water downhill, but also surface runoff that is caused by saturation from below. As a consequence, the runoff volume for a given storm will increase as compared to the events occuring earlier in the wet season when soil water contents were lower. The increase of the 'Curve Number' during periods of high soil moisture (see Fig. 3 of Calvo *et al.,* 2005, this volume) supports this hypothesis.

The increasingly higher quasi-stable base flows reported by Niedzialek and Ogden (2005, this volume) can be explained, at least in part, by inspecting the experimental work by Hewlett and Hibbert (1963). The more moist the soil, the higher the unsaturated hydraulic conductivity and, therefore, the higher the unsaturated flow parallel to the slope towards the shallow aquifer at the toe slope which feeds the stream. However, it is not clear what causes the step-wise increase in base flow during the wet season. This may be a caused by the soil hydraulic properties and/or components of saturated ground water flow.

Niedzialek and Ogden (2005, Chapter 10) observed that the runoff behavior for the upper Río Chagres basin differs from that in the Río Piedras sub-basin. They discuss possible causes for the almost ephemeral flow regime of the Río Piedras, including the contributions of ground water to base flow and the change in land use that has occurred on part of the Río Piedras catchment. Another possible cause is the unsaturated flow regime along the hill slope. A small difference in soil moisture storage and/or unsaturated hydraulic conductivity could easily lead to a dramatic stop of baseflow during the dry season and between storms. Harrison *et al.* (2005, Chapter 7) observed that the soils at the Piedras site are much thinner that those in the Chagrecito site. If this observation holds for the entire upper Chagrecito and Piedras sub-catchments, then it would indicate that soil moisture storage in the upper Río Piedras sub-catchnment is much less than in the upper Río Chagrecito sub-catchment. As a consequence, the water level of the upper Río Chagres watershed falls dry in the dry season due to a lack of water supply by unsaturated flow down the hill slope.

6. RESEARCH NEEDS

Much progress has been made with the development of a conceptual model that describes all aspects of runoff production in the upper Río Chagres watershed. However, more research is required to quantify all components of the runoff process and verify the conceptual model and hypotheses posed in Sections 4 and 5 of this paper. Specifically, we see the following research needs:

(i) Determination of (i) exactly how and over what distance macropores and soil pipes are connected, (ii) if soil pipes and macropores start at the soil surface or inside soil profile, and (iii) what is the connection between pipes and small surface depressions.

(ii) Measurement of runoff rates to study the occurrence of Hortonion runoff due to lower infiltration rates caused by water repellency and a measurement of infiltration rates to investigate the effects of macropores and cracks.

(iii) Determination of the degree of water repellency in the field as a function of soil moisture, air temperature, and relative humidity.

(iv) Determination of what part of dry season base flow is a result of soil drainage (unsaturated subsurface flow) and what part is from inflowing ground water (saturated subsurface flow) in order to quantify how future groundwater exploitation in the basin will affect base flow.

(v) A hydrologic characterization of the behaviour of aquifers underlying the upper Río Chagres basin and the amount of ground water recharge, about which little is presently known. Since these aquifers are an important and accessible source of water during periods of water scarcity in El Niño years, their assessment should have a high priority.

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