The effect of rainfall, slope gradient and soil texture on hydrological processes in a tropical watershed

Baumann, J.[1] – Rodríguez Morales, J.A. – Arellano Monterrosas, J.L.

[1]National Water Commission (CONAGUA), Av. Insurgentes Sur 2416 Piso 6, Col. Copilco El Bajo, 04340 México, Distrito Federal. Tel.: (++52) 55 51744160, Fax: (++52) 55 51744162, E-mail: jh_baumann@web.de

1. Abstract

Runoff measurement at three investigation sites in the Huehuetán watershed showed that physical soil properties as well as slope gradient are key factors to control rainfall – runoff response at micro-catchment scale. Deep weathered soils in granitic saprolite are characterized by a high rainfall absorption capacity. During tropical rain accumulations over a period of several consecutive days, the progression of the soil humidity front and deep subsoil saturation influence strongly the runoff behavior on soils with coarse texture. Rainstorms up to 70mm generate more runoff on moderate slopes (10%) with heavy clay soils, than on steep slopes (50%) with a sandy clay loam texture. Beyond this threshold value and with growing rain amount of single storm events, the influence of slope gradient as a controlling factor on micro-catchments runoff behavior will prevail. The overall statistical analysis indicated that runoff behavior is well correlated with rain parameters that combine rainfall amount and intensity characteristics like the EI_{30} and the AI_{30} indices.

2. Introduction

Hydrological processes in tropical watersheds are strongly influenced by particular climatic, geomorphologic and soil conditions in the tropics (Bonell 2007). Rain amount and rainfall intensities are commonly much higher than in temperate regions. High temperature and wetness accelerate rock weathering and the formation of deep soil profiles is widely shown in the tropics. Recently there is a major focus on soil physical properties, geological aspects and topographic conditions as key factors which control runoff response in tropical catchments under extreme rainfall patterns (Bruijnzeel 2004, Noguchi et al. 2005).

In the Huehuetán watershed in the Tropical Pacific Coastal Region of the State of Chiapas, Mexico, strongly weathered granites form the principal geologic basement. In the middle and upper parts of the watershed, soils are influenced by volcanic ashes from the Tacaná and Santa Maria volcano. Downstream the foothill area is dominated by clayey soils. The region is characterized by mean annual rainfall amounts that range from 1200mm in the lower coastal zone up to 4500mm in the middle parts of the watershed between 500 and 1400 masl. Rain ersovity (EI_{30}) and maximum intensities of single rains can vary widely within each rainstorm class. All rains of more than 80mm are extremely erosive and occur frequently every year.

3. Investigation sites and methods

At three investigation sites four micro-catchments were selected with mean slope gradients of 10 % (UNACH, pasture), 33% and 46% (Argovia farm, Coffee plantation) and 50 % (Cecilia farm, Maize-fruit trees). Each micro-catchment was equipped with rain recorders type Hellmann and standardized H-flumes with Stevens F-type water level recorders providing peak discharge and total direct runoff. Soil charcaterization included soil profile description, soil texture, porosity and pore size distribution analysis. Soil moisture was measured with a TDR Moisture Point 917 system along fixed vertical probes to a maximum depth of 120cm.

Table 1 Study sites and micro-catchments in the Huehuetán watershed

Site	**Altitude a.m.s.l.** (m)	**Production system**	**Catchment area** (ha)	**Mean slope gradient** (%)	**Annual rainfall** (mm)
Argovia farm	620	CP	1.7	33	4277
Argovia farm	620	CPT	2.8	46	4277
Cecilia farm	322	AFMF	3.4	50	3334
UNACH	60	PA	8.5	10	1256

UNACH: Experimental site of the Chiapas University; CP: Coffee plantation; CPT: Coffee Plantation with individual terraces; AFMF: Maize with fruit trees; PA: Pasture

4. Results

4.1 Rain effects

An important factor for runoff response in the micro-catchments is the occurrence of rainfall accumulations. Rain accumulations over a period of three or four days with more than 200mm rainfall occur with annual frequency in the watershed. The runoff coefficient during such events can increase up to 0.5, and soil moisture measurements revealed that the soil humidity front and soil water saturation advance to the deep subsoil. As an example the runoff behavior of extreme rain accumulations between 07^{th} - 14^{th} October 2004 at Argovia farm are presented in table 2. The four storm events between October 7^{th} and 10^{th} provided a rain total of 341mm and elevated soil moisture content in the subsoil (< 60cm) up to the saturation point (> pF 1.8) (Fig. 2), meanwhile the upper horizon still maintained a small storage capacity (Fig. 1). Regardless the high rainfall amount, percentage of runoff was low and ranged only from 2.1% to 12.1%. During the following storm event on October 12^{th} runoff raised up extremely to 20.0 (CP) and 40.7 % (CPT). This high level was maintained over the following two days and reached maximum values of 47% (CPT) and 50% (CP) on October 14^{th} (table 2).

Table 2 Rainfall accumulation and runoff between October 7^{th} and 14^{th} at Argovia farm

Date	Rainstorm mm	EI_{30} $N\ h^{-1}$*	I_5max mm/h	Runoff CPT mm	Runoff CPT %	Runoff CP mm	Runoff CP %
071004	107.9	207.2	137.5	9.3	8.6	8.6	8.0
081004	110.0	345.6	146.9	13.3	12.1	9.6	8.7
091004	82.3	103.7	97.5	5.4	6.6	8.5	10.3
101004	40.8	27.9	61.3	3.7	9.1	0.9	2.1
121004	120.6	465.1	193.8	49.1	40.7	25.2	20.9
131004	65.8	133.8	197.5	22.0	33.4	--	--
141004	93.3	157.4	95.0	41.2	44.1	47.0	50.3

* Conversion factor to (MJ mm)/(ha hour): 10

The behavior of runoff along this rain accumulation reflects the elevated capacity of the deep weathered soil at Argovia farm to absorb high rainfall amounts of consecutive erosive storms over several days. However there seems to be a threshold point depending on both the saturation of upper soil horizon and the depth of subsoil saturation. This underlines the observation of Kusumastuti et al. (2007) that soil depth and the percolation and drainage conditions in the subsoil are important controlling factors of runoff response.

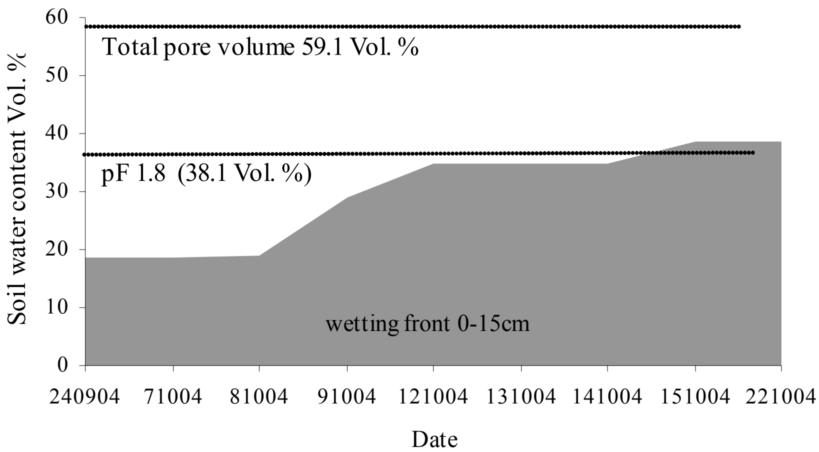

Figure 1 Development of soil moisture content and soil humidity front in 0-15 cm soil layer

The statistical analysis for the relationship between rainfall and runoff indicated that single short term maximum intensity parameters did not explain very well runoff behavior at the microcatchment level. Runoff is much better correlated with parameters that combine rainfall amount and intensity characteristics as the EI_{30} and the AI_{30} (product of rain amount and maximum 30-minutes intensity of the storm event) indices. Nevertheless, also rainfall amount as a single parameter provided a good correlation with runoff.

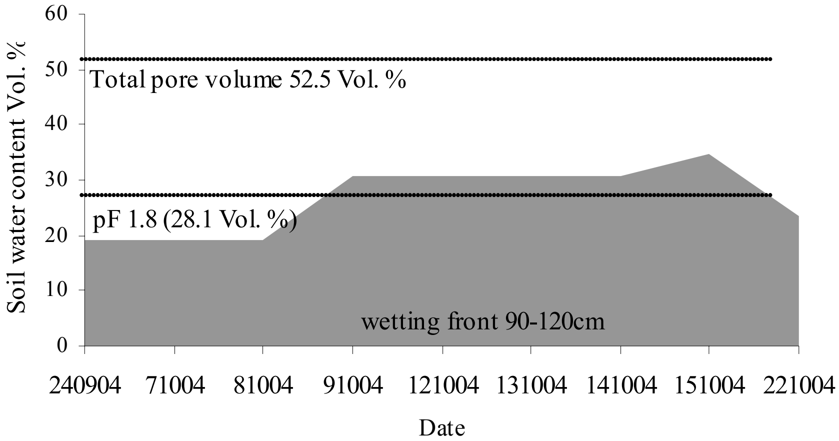

Figure 2 Development of soil moisture content and soil humidity front in 90-120cm subsoil

Slope and soil texture effects

The soils at the three investigation sites comprise a wide range of texture groups. At Argovia farm sandy loams and loamy sands are dominant, meanwhile at Cecilia farm a Cromic Cambisol with a sandy clay Loam in the upper horizon and clay content about 50 % in the subsoil form the principal soil type in the microcatchment. The most clayey soil is the haplic Acrisol at UNACH site with 82% clay content in the subsoil (table 3).

Table 3 Soil type, texture and field capacity of topsoil and subsoil horizons

Site	Soil type	Horizon	Sand (%)	Silt (%)	Clay (%)	Texture class
Argovia	haplic	Ah	69	14	16	sandy Loam
	Arenosol	Cw	77	12	11	loamy Sand
Cecilia	cromic	Ah	38	25	37	sd. clay Loam
	Cambisol	Cw	31	18	51	sandy Clay
UNACH	haplic	Ah	17	25	58	clay Loam
	Acrisol	B3	9	9	82	Clay

The mean runoff coefficients (RC) varied from 0.06 (CP) and 0.092 (CPT) at Argovia farm to 0,216 at Cecilia farm. At the UNACH site mean RC was 0.196. For each microcatchment rainfall – runoff curves were established, displaying the development of mean runoff with increasing rainfall amount (Fig. 1-2). The direct comparison of the two catchments at Argovia farm made possible the measurement of the effect of slope gradient on runoff. The average runoff will increase by about 40% when mean slope gradient ascends from 33% to 46%. During highly erosive single storm events this difference can be more than double.

The comparison of the rainfall – runoff curve from Cecilia farm steep slope (50%) microcatchment with the curve from UNACH microcatchment revealed that rainstorms up to approximately 70mm generate more runoff on moderate slopes (10%) with heavy clay soils, than on steep slopes with a sandy clay loam texture. Beyond this threshold range and with growing rain amount of single storm events the influence of slope gradient as a controlling factor on microcatchment runoff behavior will prevail. This conclusion is deduced under the supposition that the dense ground cover of the well established pasture system provides a good protection against erosion and runoff processes as well as the maiz-fruit tree system at Cecilia farm. Comparing the steep slope catchment at Argovia farm (CPT) with the steep slope catchment at Cecilia farm (AFMF), the difference in runoff behavior seems to reflect a combined effect of soil texture and vegetation type.

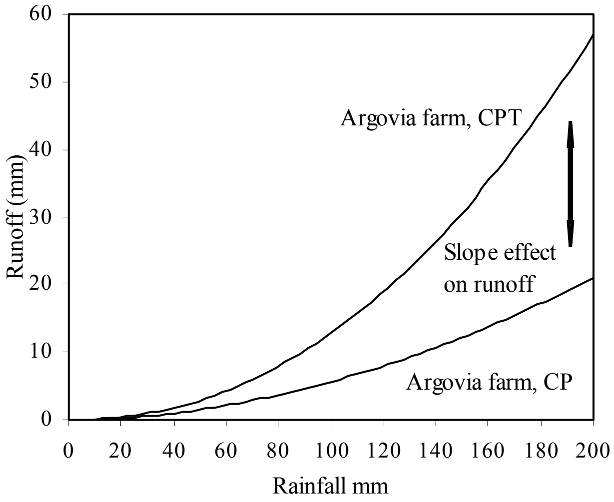

Figure 3 Rainfall – runoff curves for micro-catchments at Argovia farm

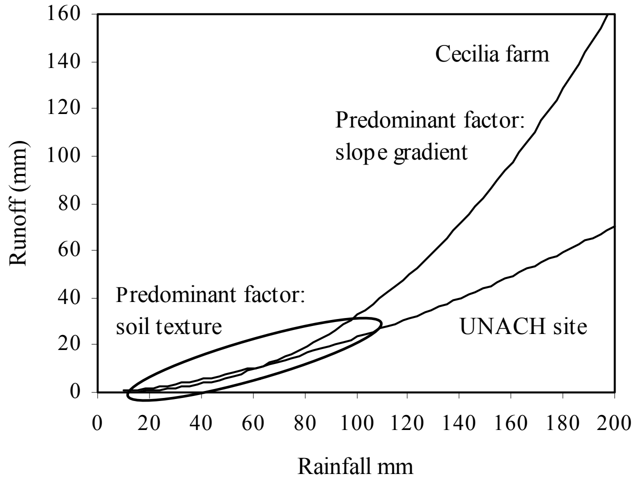

Figure 4 Rainfall – runoff curves for the Cecilia farm and UNACH microcatchments

5. Conclusions

Rainfall – runoff processes in tropical microcatchments are driven by a combination of factors like rainfall characteristics, soil physical conditions, slope gradients and vegetation types. Nevertheless, soil physical properties like texture and drainage conditions of the subsoil as well as slope gradients are key factors in runoff control under tropical rainfall with high storm event intensities and rainfall accumulations.

References

Bonell, M., 2005. Runoff generation in tropical forests. In: M. Bonell, L.A. Bruijnzeel (Editors): Forests, Water and People in the Humid Tropics. International Hydrology Series. Cambridge University Press, pp. 314-406.

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees. Agriculture, Ecosystems and Environment, 104: 185-228.

Kusumastuti, D.I., Struthers, I., Sivapalan, M., Reynolds, D.A., 2007. Threshold effects in catchment storm response and the occurrence and magnitude of flood events: implication for flood frequency. Hydrol. Earth Syst. Sci., 11: 1515-1528.

Noguchi, S., Nik, A. R., Tani, M., 2005. Runoff characteristics in a tropical rain forest catchment. JARQ, 39 (3): 215-219.