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Rainfall/runoff processes in a small peri-urban catchment in the Andes mountains. The Rumihurcu Quebrada, Quito (Ecuador)

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Abstract:

Situated at the foot of the Pichincha volcano, the city of Quito is frequently subjected to hydroclimatic hazards. In 1995 an 11·2 km^2 watershed, located in the vicinity of the city, was equipped with eight rain gauges and two flow gauges to better understand the local rainfall/runoff transformation processes. Rainfall simulation experiments were carried out on more than 40 one-square-metre plots to measure infiltration point-processes. The high density of measurement devices allowed us to identify the origin and nature of the various contributions to runoff for the different physiographic units of the watershed: urban area from an altitude of 2800 to 3200 m; farmland, pasture and forested land, and finally *páramo* above 3900 m. Runoff occurs mainly in the lower part of the basin and is caused by urbanization; however, the natural soils of this area can also produce Hortonian runoff, which is predominant in a few events. This contribution can be studied through rainfall simulation experiments. In the upper natural zone, the younger and more permeable soils generate less runoff on the slopes. However, almost permanently saturated contributing areas, which are located in the bottom of the *quebradas*, may generate flood events, the size of which depends on the extent of the area concerned. Variations in the runoff coefficients are related first to the baseflow and second to the amount of rainfall in the previous 24 h. This analysis, which underlines the complexity of a small, peri-urban, volcanic catchment, is a necessary preliminary to runoff modelling in an area where very few experiments have been carried out on small catchments. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS rainfall/runoff processes; volcanic soils; urban area; Quito; Ecuador; Andes

INTRODUCTION

Quito is located on a S–N oriented fault step that occurs along the edge of the inter-Andean valley, at a mean elevation of 2800 m above sea level (Figure 1). To the west, the city is dominated by two volcanoes, Pichincha (4627 m) and Atacazo (4455 m).

Numerous ravines, named *quebradas*, deeply gash the slopes of the Pichincha volcano, which are covered with thick layers of ash deposited by past eruptions. They delimit catchments that are often very long in shape and cover areas ranging from a few hectares to several square kilometres, with slopes frequently greater than 20° or even over 30°. On the east side of the Pichincha, more than 30 *quebradas* directly intersect the sewage network of the city, and may generate floods, mud flows and debris flows during the heaviest rainfall (Peltre, 1989). Over the last few years, urbanization has progressively covered the lower slopes of the volcano, which used to be protected. As a result of the increase in impermeable land, the situation has become more hazardous for the populated areas downhill.

Hydrological studies of volcanic catchments have been carried out in other parts of the intertropical zone, in particular in tropical islands (Guiscafré *et al.*, 1976; Chaperon *et al.*, 1985; Ferry, 1988; Depraetere and

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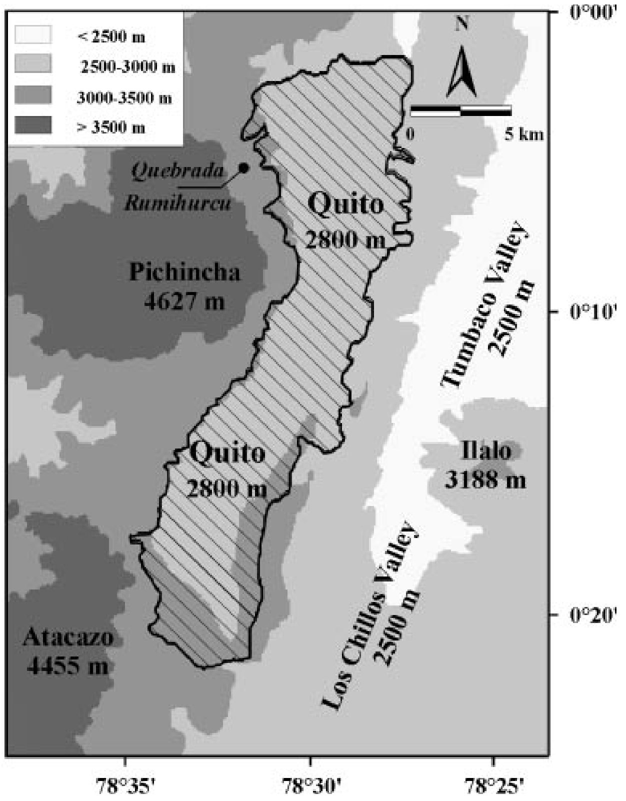

Figure 1. The study area

Moniod, 1991; Diaz *et al.*, 1995). However, these studies are either very descriptive or focus on other aspects than runoff. To our knowledge, the only study that deals with hydrological runoff processes on small catchments concerns the island of Tahiti (Wotling, 2000), where runoff was found to be caused by Hortonian and contributing-area processes. However, the pluviometrical and geomorphological characteristics cannot be compared *a priori* with conditions prevailing in Quito or in other big mountain cities on the American continent—from the Andes cordillera to the Mexican Sierra Madre.

As the hydrological processes in the mountain slopes were practically unknown, an experimental network was installed in 1995 on the catchment of the *quebrada* Rumihurcu (Perrin and Ayabaca, 1996), located at the upper periphery of Quito (Figure 1). This 11·2 km^2 catchment was chosen because it assembles most of the physiographic characteristics found on the slopes of the Pichincha. The objective of this paper is to characterize the different runoff processes on this catchment, and to provide a first interpretation of the results.

DESCRIPTION OF CATCHMENT

Physical features

The elevation of the catchment ranges from 4627 m (Rucu Pichincha) to 2900 m. It has an andesitic-type basement, due to the numerous volcanic emissions that have occurred in the past. The slopes are irregular, shaped by glacial and periglacial processes, and deeply cut by many small tributary gullies (Figure 2).

From November 1996 to October 1997, precipitation over the catchment varied from about 1100 mm to more than 1700 mm, depending on altitude. As is typical of a high-altitude tropical climate, rainfall is not

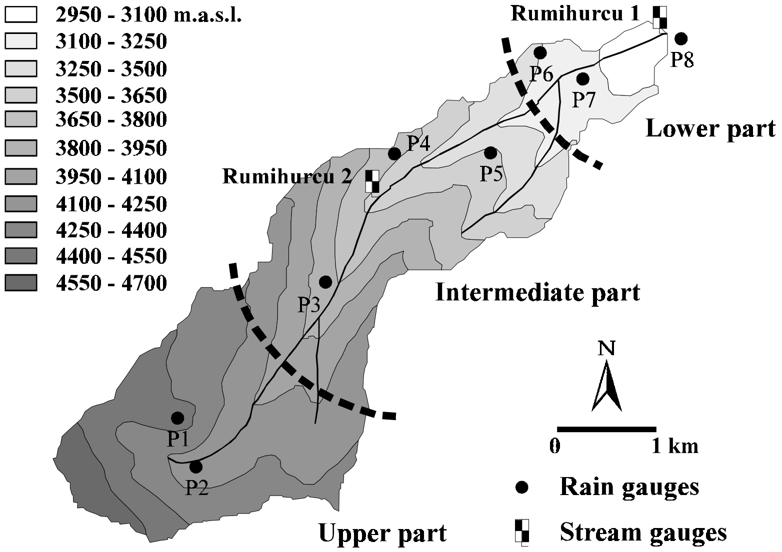

Figure 2. General topography and experimentation network—Rumihurcu catchment

very intense: at an altitude of 2800 m and for a 10-year return period, daily rainfall was about 60 mm, and maximum intensity over a 5-min period was around 100 mm $\cdot$ h^{-1}. It is worth noting that rainfall intensity decreases with altitude, while rainfall amount increases (Bouvier *et al.*, 1999).

The catchment is composed of three main areas (Cisneros, 1997):

- above 3900 m, at the foot of Pichincha summit, the upper part of the basin is relatively open (Figure 2), covered with herbaceous, *páramo*-type vegetation (Figure 3), with gentle slopes in and around the main talweg (5–10°);

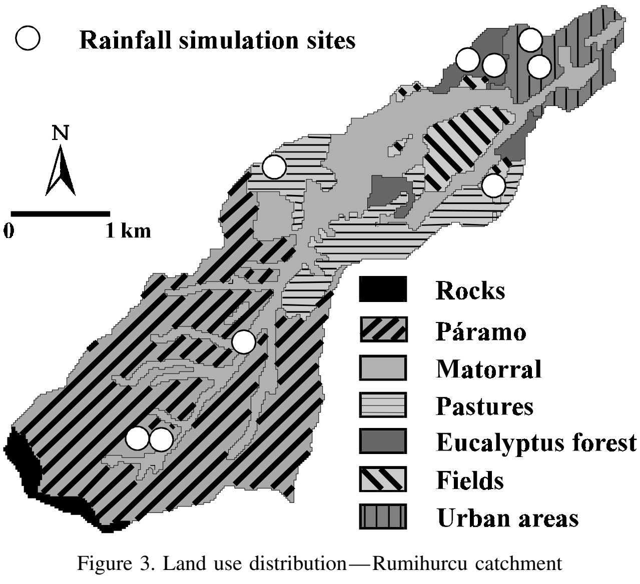

Figure 3. Land use distribution—Rumihurcu catchment

- from 3900 to 3200 m, in the intermediate part of the catchment, the *quebrada* is very deep (Figure 2), hemmed in by steep slopes (sometimes over 70°) covered with endemic *matorral* shrub vegetation (Figure 3). The upper parts of the slopes are used for farming (potatoes, broad beans) and pasture;
- below 3200 m, the lower part is mainly an alluvial fan-shaped area, also deeply cut by the *quebrada* and covered by what is left of an eucalyptus forest, farmland and uncontrolled urbanization (Figure 3) that extends over the whole lower part of the catchment.

The types of soil vary with the altitude of the catchment. In general terms, there are unconsolidated soils above recent ashes and volcanic tuffs in the upper and intermediate basin; these are mainly composed of andisoils containing allophanes; sandy-silt regosoils appear at an altitude of 3300 m; in the lower part, i.e. below 3200 m, morainic deposits can be found, though the most representative formations show thick indurated horizons of volcanic ash soils (*cangahua*).

The organization and main characteristics of these soils could be deduced from laboratory analysis of undisturbed samples (about 50), studies of pedological cuts (32) and geo-electric proofs (15) made in the basin (Poulenard, 1996; Janeau *et al.*, 1997; Risser, 2000). The granulometric data were obtained through the analysis of samples taken every 10 cm from the surface to a depth of 1 m for each different type of soil. Bulk density and water retention data were obtained through the analysis of five undisturbed samples for each different type of soil.

- Above 3900 m (*páramo*-type vegetation), stratification of soil and of superficial formations is very homogeneous. On the slopes, first there is a layer of soil (50 cm deep, clay 6%, silt 34%, sand 60%) over a thin layer of pumice (10–15 cm deep, clay 7%, silt 17%, sand 76%) with a high proportion (50%) of coarse elements (diameter >1 cm), and then a recent layer of ashes (150 cm deep, clay 7%, silt 30%, sand 63%). At the bottom of the slopes, the same layer of soil is found over a layer of compacted colluvium (70 cm deep, clay 17%, silt 58%, sand 25%).
- Between 3900 and 3200 m we can distinguish the following. The steep slopes of the *quebrada* (*matorral* shrub vegetation), where there is a layer of organic soil (120 cm deep, clay 6%, silt 10%, sand 84%) that lies directly on the andesitic basement or its alteration horizon. The upper parts of the slopes (farmland and pasture), where the top metre of soil shows a vertical differentiation in texture (clay 7%, silt 30%, sand 63% at the top of the profile and clay 7%, silt 18%, sand 75% at a depth of 1 m).
- Below 3200 m, the most representative formations show a layer of organic soil (30 cm) over thick indurated horizons of volcanic ash soils (clay 10%, silt 10%, sand 80%) named *cangahua* that are more than 12 000 years old (Zebrowski, 1997).

In the upper part of the basin, and in superficial horizons (0–50 cm), the water content of the soils (obtained with the membrane press method on undisturbed samples) is very high, with values ranging between 0·65 cm^3/cm^3 at saturation and 0·40 cm^3/cm^3 at wilting point. The bulk density is very low, with values ranging from 0·8 to 1·0. These two facts that characterize the andisoils are due to the presence of allophanes and organic matter (20%) in the profile. Associated with a micro-aggregated structure, these characteristics give the soils a high infiltration capacity. The presence of a pumice layer with very high conductivity due to the coarse texture of the material very likely increases the infiltration capacity of this formation and could induce lateral transfer of the water to the lower part of the slope. In the lower part of the basin, the water content of the *cangahua* is very low, with values ranging between 0·25 cm^3/cm^3 at saturation and 0·10 cm^3/cm^3 at wilting point. The bulk density varies between 1·3 and 1·5 and the organic matter content is very low (<5%). These characteristics, associated with an indurated structure, give the soils a very low infiltration capacity.

Experimental design

To understand the behaviour of this heterogeneous catchment, and in particular to quantify the hydrological contributions from the upper basin (natural area) and from the lower basin (urbanized area) (Figure 2), two flow gauging stations were built in the main stream (Figure 1).

- The downstream gauging station (Rumihurcu 1) collects about 90% of the catchment runoff before it enters Quito's sewage system. It is located at an altitude of 2920 m, just downstream from a stabilization reach and controls the output from an 11·2 km^2 catchment area.
- The second gauging station (Rumihurcu 2) is located upstream, at an altitude of 3280 m, and controls the output from a 7·5 km^2 catchment area.

To estimate the spatial distribution of rainfall, a network composed of eight rain gauges was installed on the catchment, in a transect that ranges from 4200 to 2900 m in altitude (Figure 2).

To supplement this network, and to better understand infiltration processes that occur throughout the catchment, several rainfall simulations were carried out on one-square-metre plots. The simulations were performed on various units (Figure 3), using an ORSTOM mini-rainfall simulator (Asseline and Valentin, 1978). The intensity of each simulated rainfall was increased from 20 to 120 $\text{mm} \cdot \text{h}^{-1}$ during the 90-min duration of the event. Four rainfall events were conducted on each plot, at an interval of a few hours. This experimental protocol allowed us to characterize infiltration for a large range of rainfall rates and soil moisture conditions. A large proportion of our experimentation was centred on the most representative physiographic units, namely, *páramo* with steep slopes and *páramo* with gentle slopes in the upper part of the basin (10 plots), and bare semi-urbanized areas and vegetation-covered areas in the lower part (15 plots).

RAINFALL/RUNOFF PROCESSES IN THE CATCHMENT

General

Around 60 floods have been registered since the installation of the network. In general, associated precipitation is limited in extent and does not cover the whole catchment. This is an advantage in the study of the hydrological behaviour of each of the three units of the catchment. In some cases when effective rainfall covers the whole catchment, typical flood characteristics at the downstream station (Figure 4) show an initial peak that originates in the lower area, followed by a flood recession period, and finally a second but smaller peak that originates in the upper area. Thus, even in these cases, the hydrological behaviour of each unit can be characterized independently.

The flood recession period shows that there is no runoff contribution either from the intermediate *matorral*-covered areas or from pastures and farming areas on the steepest slopes of the *quebrada* situated between 3900 and 3200 m. Furthermore, in the major rainfall events that occurred in the P3 and P4 zones, no runoff

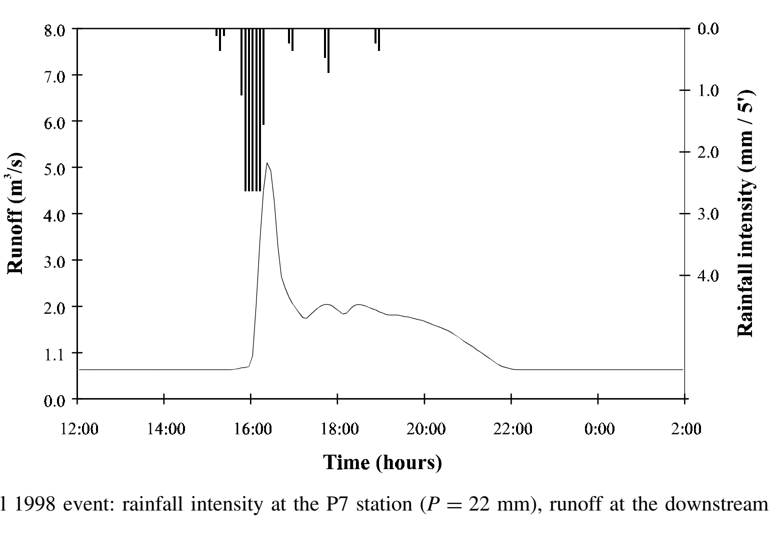

Figure 4. The 19 April 1998 event: rainfall intensity at the P7 station ($P = 22$ mm), runoff at the downstream station Rumihurcu 1

was measured at the gauging stations. So runoff production is limited to the upper zone (above 3900 m) and the lower one (below 3200 m).

Rainfall simulation results enabled us to demonstrate the high variability of the infiltration processes depending on each hydrological unit. Two parameters were chosen to characterize the rainfall simulation results: infiltration intensity (Inf in mm · h^{-1}) obtained in steady flow conditions, and preponding rainfall (Pr in mm), which is rainfall depth before the beginning of runoff during the simulation (Figure 5).

In the *páramo* zone of the upper part of the basin, the results of rainfall simulations are consistent for the 10 different plots.

- For the slopes (which represent 80 or 90% of this zone), we obtained 20–30 mm preponding rainfall and 50 mm · h^{-1} infiltration intensity (Figure 5).
- For the bottom of the slope and flat zone near the main stream where there are permanently saturated areas, we obtained 5–10 mm preponding rainfall and infiltration intensity may reach 0 mm · h^{-1} due to saturation excess.

In the lower part of the basin, runoff from natural *cangahua* soils depends on the density of vegetation. On bare soils, preponding rainfall varies between 5 and 10 mm and infiltration intensity between 10 and 20 mm · h^{-1}. On vegetation-covered soils, preponding rainfall varies between 10 and 30 mm and infiltration intensity between 10 and 20 mm · h^{-1}. In such natural areas, even vegetation-covered ones, Hortonian runoff is thought to be predominant.

Upper catchment (7·5 km^2)

During the 1995–1998 period, the Rumihurcu 2 station recorded 31 floods, with discharge peaks between 0·1 and 2 m^3/s. The time to peak varied from 60 to 120 min and the base time from 6 to 10 h. Given the relatively high velocity of the runoff, the origin of the floods is mainly surface runoff (Figure 6).

The runoff coefficients C_r (runoff depth/rainfall depth in %) varied from 0·3% to 16·9%. Runoff depth was calculated from a graphic estimation without taking baseflow into account. Rain gauge P2, which was considered to be the most representative, was used to calculate rainfall depth.

Considering the infiltration values obtained from the rainfall simulation, it can be deduced that none of the rainfall events observed at rain gauges P1 and P2 could have generated Hortonian runoff on the slopes.

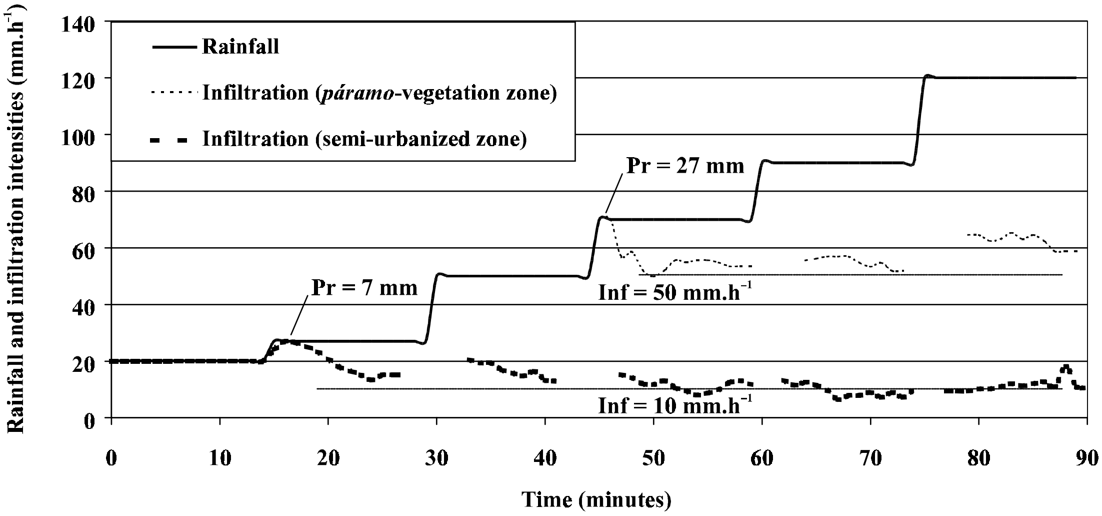

Figure 5. Rainfall simulation results for *páramo*-vegetation and semi-urbanized zones

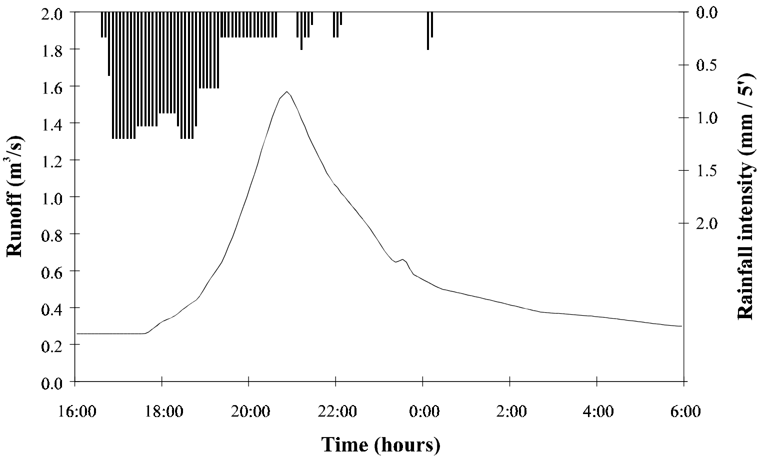

Figure 6. The 22 May 1996 event: rainfall intensity at the P2 station ($P = 32$ mm), runoff at the upstream station Rumihurcu 2

Thus, for all the studied flood events, the runoff must be the result of local saturation of contributing areas, as described by Cappus (1960), Betson (1964), Beven and Kirkby (1979) and Beven *et al.* (1984). During field visits, almost permanently saturated areas were detected in the convergence zone at the bottom of the slopes. These areas are located in the wide part of the *quebrada* above 3900 m. From a field survey, they were estimated to cover around 60 hectares (i.e. 8% of the catchment area). The comparison of this estimation with the range of observed runoff coefficients is coherent.

Furthermore, it is possible to link, although rather loosely, variations in the runoff coefficient with variations in baseflow (Figure 7). Such a relation was shown by Kirkby and Chorley (1967), Moore *et al.* (1986), Ambroise (1988) and Grésillon and Taha (1998). To refine this relation, other variables were introduced, the most effective being rainfall during the previous 24 h (P_{pre}).

A quite good adjustment (Figure 8) is then obtained between the runoff coefficient C_{r} (%), and the baseflow Q_{b} (l/s) at the beginning of the event and rainfall over the previous 24 h P_{pre} (mm), using the relations:

$$C_{\mathrm{r}}(\%) = 0{\cdot}16 \cdot A + 0{\cdot}01 \cdot B + \mathrm{Cst} \tag{1}$$

$$\text{with } A = \exp^{(0{\cdot}013 \cdot Q_{\mathrm{b}})},\ B = P_{\mathrm{pre}}^2 \text{ and Cst between 1 and 2.}$$

This model explains 80% of the variance of C_{r}, 50% and 30% of those of A and B, respectively. These two variables are independent (with a correlation coefficient $R < 0{\cdot}1$), even taking into account the high autocorrelation of Q_{b}.

These two variables suggest two different processes for the saturation of the contributing areas.

- The first process, linked to variations in baseflow, is due to the lateral component of subsurface flow all along the hillslopes (these transfers may be facilitated by the pumice layer, which is inserted into the ash layers and has higher hydraulic conductivity) and/or groundwater flow at the interface of superficial formations and the impervious andesitic basement. To estimate the mean travel-time, correlations were made between the baseflow and the moving average of rainfall amounts over N days. The best result was obtained with $N = 7 (R = 0{\cdot}70)$. Consequently, a 7-day travel-time could be adopted for the hillslope soils.
- The second process, with a shorter response time, concerns the influence of rainfall events that occur within the previous 24 h. Through phenomena of local saturation, it compensates for the small deficit in soil water that may exist in the soils located near the main drain. This effect mainly applies to the lower values of the runoff coefficient, but may also affect higher values.

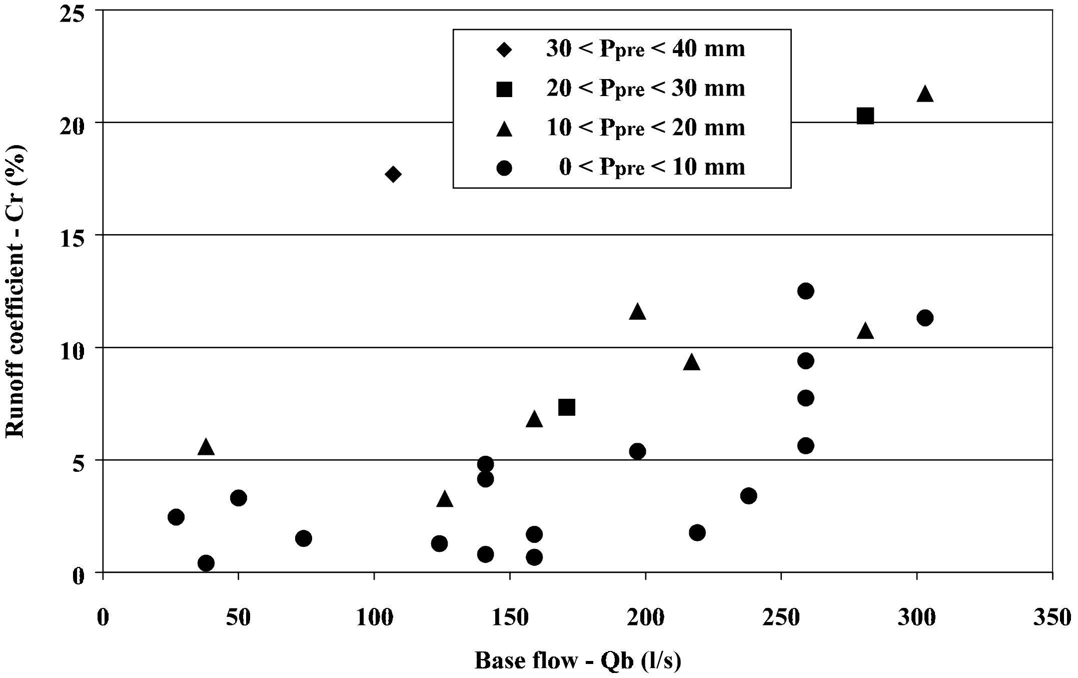

Figure 7. Runoff coefficient as a function of baseflow and rainfall in the previous 24 h (upper catchment—Rumihurcu 2)

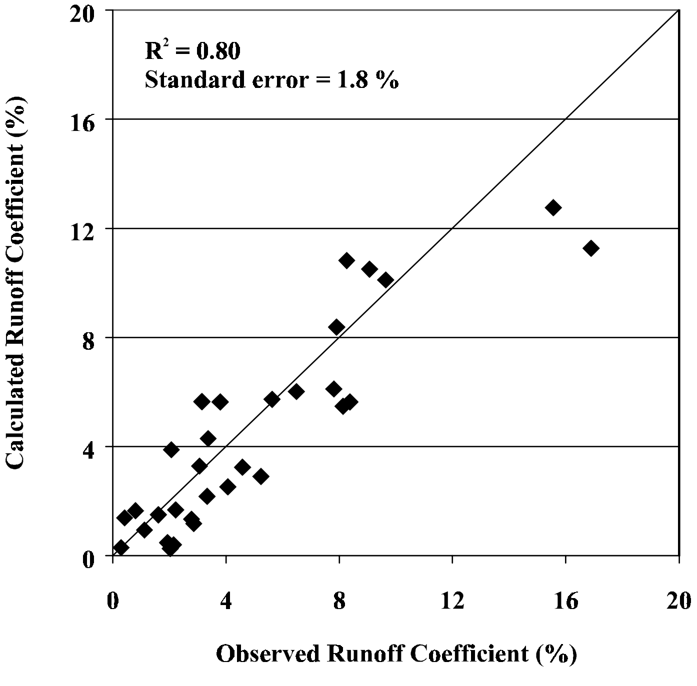

Figure 8. Observed and calculated runoff coefficients (upper catchment—Rumihurcu 2)

Lower catchment (3·7 km^2)

The lower basin covers the area located between the two gauging stations. The upper part of the lower basin (above 3200 m) is made up of steep slopes with permeable soils, which are assumed not to produce runoff. Hence, the active area can be considered to be limited to the *cangahua*-type soil covering a two-square-kilometre area situated below 3200 m. In this part of the basin, urbanization decreases uphill, and the unbuilt zones are generally covered with vegetation. The density of urbanization (i.e. the ratio between first, real built-up areas, bare soils around urban zones, courtyards, streets, brickyards, etc., and second, the total area of the *cangahua* zone) was estimated from numerical treatment of a 1/7500 scale aerial photograph of the catchment, and gave a 20% density ratio.

The Rumihurcu 1 station registered 50 floods from 1995 to 1998. The majority had a discharge peak below 3·5 m^3/s since only five had discharge peaks of between 5 and 9 m^3/s. During rainfall events, runoff appeared rapidly, even when rainfall intensity was as low as 5 mm $\cdot$ h^{-1}. The time to peak varied from 25 to 50 min, and the time base from 2 to 4 h (Figure 4).

Figure 9 shows runoff depths against rainfall measured in the *cangahua*-type zone. For all the events during which the peak flow did not exceed 3·5 m^3/s, the runoff coefficient appears to be uniform (see the straight line in Figure 9) at around 15%, a value that nearly corresponds to the density of urbanization. This kind of behaviour, i.e. low variability in the runoff coefficient whose value approaches the density of urbanization, is known to be typical of urbanized areas (Arnell, 1982; Desbordes, 1987; Boyd *et al.*, 1993; Brulé *et al.*, 1997). Natural soils did not produce any runoff in the range of events considered.

Nevertheless, this model greatly underestimates runoff depths for floods with discharge peaks over 3·5 m^3/s. Given the low spatial variability of precipitation over this part of the catchment (which is particularly true of the biggest rainfall events), this increase in runoff is therefore due to an additional contribution from natural vegetation-covered zones with *cangahua*-type soils. Additional indications were obtained regarding the characteristics of the main rainfall/runoff events (Figure 9).

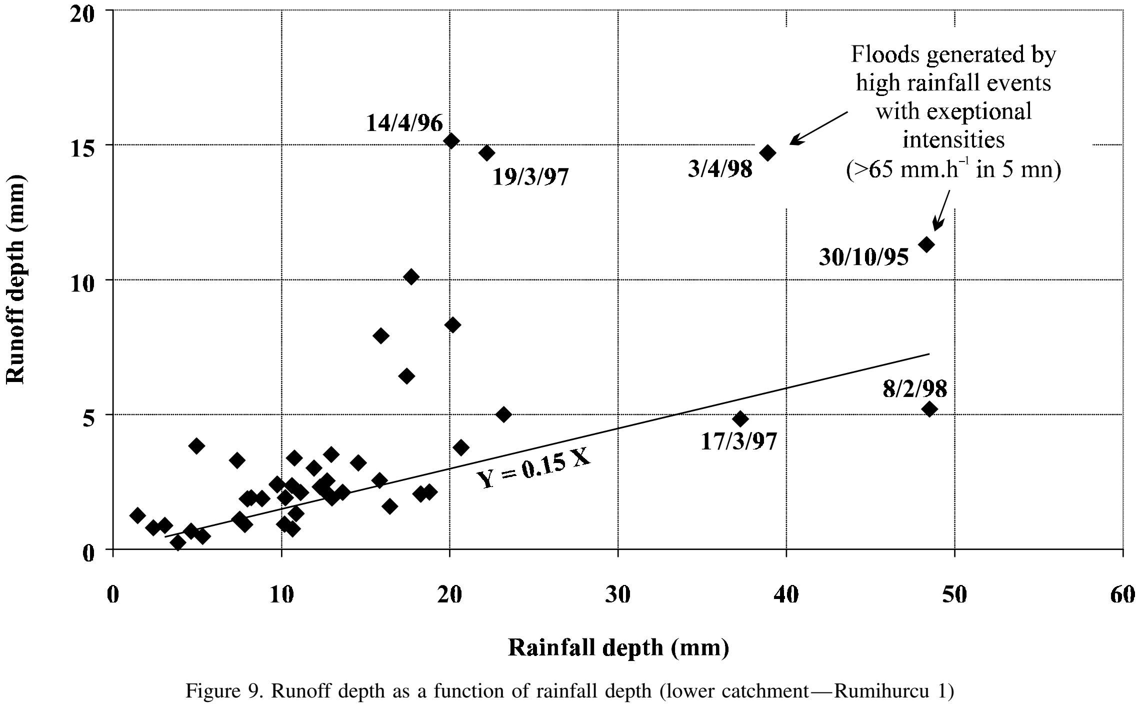

Figure 9. Runoff depth as a function of rainfall depth (lower catchment—Rumihurcu 1)

- The occurrence of runoff from the natural part of the catchment may be linked to highest rainfall intensities and amounts: for example both the 30/10/95 and 3/4/98 flood events generated the highest discharge peaks (nearly 10 m^3/s), while the rainfall intensities and amounts were greater than 65 $mm \cdot h^{-1}$ and 35 mm, respectively.
- The previous rainfall seems to play a major role: runoff caused by moderate rainfall amounts increases if the soil moisture conditions are high (events $14/4/96 - P = 20$ mm and $19/3/97 - P = 22$ mm); conversely, runoff caused by bigger rainfall amounts may be considerably reduced if soil moisture content is low (events $17/3/97 - P = 37$ mm and $8/2/97 - P = 50$ mm); this occurs at the very beginning of the rainy season after more than two dry months.

We then tried to adjust a model to compute runoff amounts. The contribution of the urbanized area was computed using a single runoff coefficient of 0·20, which can be assumed to be the density of urbanization; thus we have:

$$P_n(\Delta t) = 0{\cdot}20 \cdot P_b(\Delta t) \tag{2}$$

where $P_b(\Delta t)$ and $P_n(\Delta t)$ (in mm) represent observed and effective rainfall amounts during a time step Δt.

For the natural area, in agreement with rainfall simulation results, a simplified Hortonian model was used, taking into account runoff losses due to initial storage in a soil reservoir (parameter STO in mm) and a constant infiltration rate (parameter INF in $mm \cdot h^{-1}$). The effective rainfall during time step Δt was expressed as:

$$P_n(\Delta t) = 0{\cdot}80 \cdot [P_b(\Delta t) - \mathrm{INF} \cdot \Delta t - (\mathrm{STO} - \mathrm{stoc}(t))] \tag{3}$$

where stoc(t) (in mm) is the level of the soil reservoir at the beginning of the time step. This level was computed in a continuous way throughout the simulation period (November 95 to November 98), using an exponential discharge function (parameter DS in h^{-1}); namely:

$$\mathrm{stoc}(t + \Delta t) = [\mathrm{stoc}(t) + P_n(\Delta t)] \cdot \exp^{(-\mathrm{DS}\cdot\Delta t)} \quad \text{if } \mathrm{stoc}(t) + P_n(\Delta t) < \mathrm{STO} \tag{4}$$

$$\mathrm{stoc}(t + \Delta t) = \mathrm{STO} \cdot \exp^{(-\mathrm{DS}\cdot\Delta t)} \quad \text{if } \mathrm{stoc}(t) + P_n(\Delta t) > \mathrm{STO} \tag{5}$$

Finally, the runoff amount was obtained by adding the effective rainfall amounts computed for urbanized and natural areas during the duration of the rainfall, and then multiplied by the area A of the catchment.

This model was calibrated from the 22 more consistent events, using time steps of 5 min. The area of the catchment was defined as $A = 2\ km^2$, which corresponds to the area where soils are of the *cangahua*-type. Except for one event, a satisfactory comparison between the observed and computed runoff amounts was obtained (Figure 10) with the following parameter values: STO = 30 mm, INF = 10 $mm \cdot h^{-1}$, DS = 0·04 h^{-1}. In the case of DS, this means that discharge for 1 h of the soil reservoir is about 4% of its capacity, 62% for one day, 85% for two days.

These parameter values can be compared with those that derive from rainfall simulation. Although this comparison would involve a more theoretical analysis that is beyond the scope of this paper, it may be noted that our first results concerning the INF parameters (10 $mm \cdot h^{-1}$) and the storage capacity of the soil reservoir STO (30 mm) are in keeping with the infiltration rate and the preponding rainfall obtained for one-square-metre plots during rainfall simulations.

This model gives a good restitution of runoff volumes for most of the modellized events. These results bring out the importance of the combination of urban runoff on built-up areas and Hortonian runoff on natural ones; in the latter, the role played by soil water content for runoff generation must be taken into account.

CONCLUSION

This study of the Rumihurcu *quebrada* highlights the diversity of hydrological processes involved in the different units of an Andean catchment, at the upper periphery of the city of Quito.

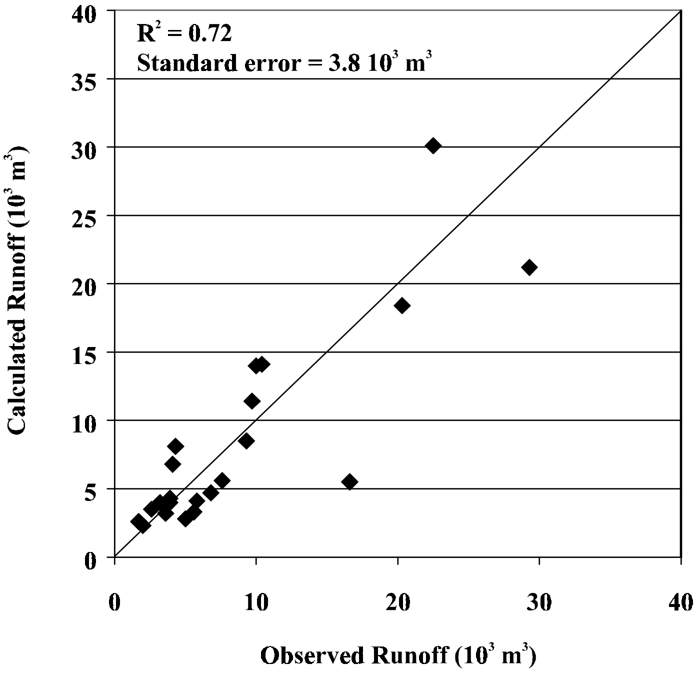

Figure 10. Observed and calculated runoff volumes (lower catchment—Rumihurcu 1)

The upper basin is mainly characterized by a high rate of infiltration through soils and ash layers. Given the permeable properties of these formations and the continuous plant cover, surface runoff is almost impossible on the slopes. Even during the rainy season, in this part of the catchment, flood generation processes are directly linked to the presence of saturated contributing areas located at the bottom of the slopes. The variables that explain the runoff volumes, namely baseflow and rainfall amounts in the previous 24-h period, suggest that the saturation processes are in fact a combination of two processes: one slow (around 7 days) and one fast (less than 24 h).

The lower basin is clearly affected by urbanization at the bottom of the Pichincha. On this part of the catchment, runoff can be accurately modelled using a runoff coefficient (around 20%) that corresponds to urban surface density. Nevertheless, the natural zones may also produce considerable runoff, either during intense rainfall events or in the case of high soil moisture content. In modelling natural runoff, there was good coherence between results obtained for the whole basin and those obtained with rainfall simulation on one-square-metre plots.

This analysis illustrates the complexity of catchments in a zone where very few experiments have previously been carried out. If the different flood generation processes are now qualitatively well known for this kind of peri-urban catchment, they need to be more precisely quantified before the results can be applied to other *quebradas*. Work is still in progress to define a complete rainfall/runoff model adapted to the spatial variability of the pluviometric and physiographic characteristics.

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