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Forests and Their Hydrological Effects in Mediterranean Mountains

The Case of the Central Spanish Pyrenees

This article considers the effects of forests on the hydrology of a Mediterranean mountain area. Variations of climate factors, discharge, interception, and water table depth in the San Salvador forested experimental catchment in the Central Spanish Pyrenees were studied and the results compared with those from two deforested catchments. The hydrological response of the San Salvador catchment had the following properties: 1) it had both smaller peak flows and smaller low flows than the deforested catchments; 2) most rainstorm events produced almost no discharge response; 3) the intensity of precipitation had no influence on the magnitude of peak flows; and 4) depth to the water table was the most important factor in the relationship between precipitation and discharge. These results confirm that forest conservation reduces floods and soil erosion, particularly on steep slopes.

Keywords: *Forest hydrology; water table; peak flows; interception; experimental catchment; Spanish Pyrenees.*

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Introduction

Water resources in Mediterranean environments depend mainly on runoff generated in mountain areas, which act as "islands of humidity" in sub-humid or semi-arid areas. Most of the population and most economic activities, including the development of large irrigated sectors, are located in the lowlands and coastal areas. This imbalance between the location of water resources and human activities gives mountain areas particular strategic importance. Streamflow is related to permanent factors (such as lithology and topography), as well as to variable, time-dependent factors such as precipitation, temperature, and land use/land cover. Changes in the variable factors can be used to explain changes in both the quality and quantity of streamflow. Thus, changes at the global scale affect not only soils, water quality, and water quantity in the mountains, but also the livelihoods and welfare of many people in the lowlands.

Forest areas play a very important role for traditional societies in the Mediterranean mountains (De la Riva 1997). In many cases original forests were burnt for the expansion of summer pastures, or replaced with cultivated fields when population density increased (García-Ruiz and Lasanta 1990). In other cases they were preserved because of local requirements for winter pastures, wood, and hunting (Puigdefábregas and Balcells 1970). Thus the primitive landscape has evolved into a complex mosaic of forests, cultivated lands, shrubs, and summer pastures, as people have tried to obtain the optimum benefit from a territory characterized by significant geo-biodiversity (García-Ruiz and Lasanta 1990).

The hydrological relevance of forests has been emphasized by many authors in the last few decades (Bosch and Hewlett 1982; Sahin and Hall 1996; Andréassian 2004; Cosandey et al 2004; Gallart and Llorens 2004; Guojing et al 2005). For instance, Hibbert (1971) and Scott and Lesch (1997) reported that reforestation resulted in a reduction of low flows. Sahin and Hall (1996) confirmed the occurrence of profound changes in the flow regime of rivers after afforestation and clearing. Beguería et al (2003) argued that the recent expansion in the Pyrenees of forests and shrubs in previously cultivated areas is the only reason for the clear decrease in streamflows in rivers not affected by water extraction. López-Moreno et al (2006) also concluded that the recent decrease in the peakflows of Pyrenean rivers is due to forest recovery, since the intensity of rainstorms has remained stable.

It is well known that land cover changes such as deforestation, reforestation, and hillslope farming alter soil properties, throughfall, and infiltration rates, which ultimately affect the hydrological cycle at the basin and hillslope scale (Goudie 1986; Hurni et al 2005) as well as soil erosion, sediment transport, and fluvial morphology (Beguería et al 2006; Hooke 2006). Forest management and conservation have a key influence on the characteristics of streamflow (Bosch and Hewlett 1982), and this is particularly important in Mediterranean mountain areas, which are characterized by strong seasonal flow contrasts, long dry periods, and intense floods. In the immediate future, the role of forests in the Mediterranean mountains will be even greater due to their expansion after farmland abandonment on the hillslopes (Vicente-Serrano et al 2004).

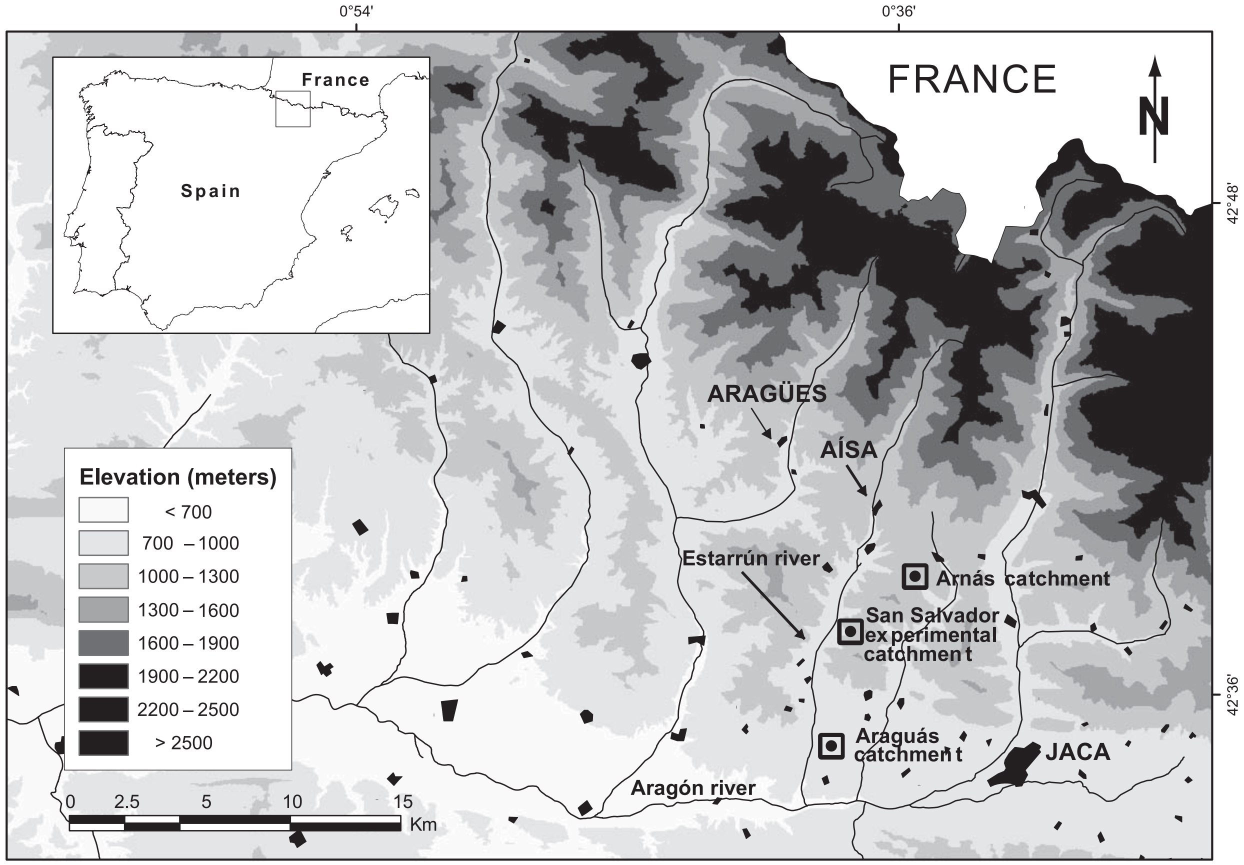
The present article discusses the hydrological response of the San Salvador experimental catchment as an example of the likely effects of forests at the basin scale in a Mediterranean mountain area. The aim of the study is to examine the hydrological behavior of well-preserved mountain environments.

Study area

The San Salvador experimental catchment

The San Salvador ravine is a tributary of the Estarrún River, in the upper basin of the Aragón River in the

FIGURE 1 Location of the San Salvador, Arnás, and Araguás catchments in the Central Spanish Pyrenees. (Map by Jesús Martínez)



central-western Spanish Pyrenees (Figure 1). The catchment is 92 ha in size, with prevailing gradients between 15 and 25°. It is located in the Eocene Flysch sector. Sandstones and marls alternate in thin beds that are strongly folded and faulted. The highest divide is at 1270 m, and the outlet is at 880 m.

The climate is sub-Mediterranean and slightly continental. Average annual precipitation is about 1100 mm at the outlet of the ravine. The rainy season takes place from October to June, though winters can be relatively dry.

The whole catchment is covered by a dense forest (Figure 2). On the north-facing slope two different environments prevail: a very dense wet pine forest *(Pinus sylvestris)*, with *Buxus sempervirens* the dominant undergrowth, and a beech forest *(Fagus sylvatica)* occupying the wetter areas, generally on concave slopes, accompanied by *Corylus avellana, Acer opalus, Tilia platyphyllos,* and *Ilex aquifolium.* On the south-facing slope, the forest is dominated by the sub-Mediterranean oak, *Quercus faginea*, with *Acer opalus* and sparse stands of *Pinus nigra.* Some old abandoned fields are now being colonized by *Quercus faginea* and various scrubs.

The soils on the north- and the south-facing slopes are different. On the former, deep and well developed Haplic Kastanozems and Haplic Phaeozems predominate, whereas Calcaric Regosols and Cambisols prevail on the south-facing slope. Under the soil, a deep, stony colluvium covers most of the slopes.

Forest distribution and management

Pyrenean forests have been exploited since at least the Neolithic period and the Bronze Age. A large deforestation period occurred around the 11th century, when the upper forest level was burnt in order to enlarge the surface occupied by subalpine grasslands, resulting in an increase in the erosion rate and in mass movements (Montserrat 1992). The lower forest level (under 1400–1600 m) was farmed first, and the intensity of forest wasting depended on demographic pressure, with the highest levels of deforestation in the mid-19th century.

In general, forests were perceived by the local population as a reserve of land, grasslands, and capital.

When farmers needed new lands for cultivation (due to population increase) they removed the trees from communal lands and opened up new fields managed with various agriculture systems even on steep slopes. If demographic pressure decreased, the fields were abandoned and, if natural conditions were favorable, they were recolonized by forests, as has occurred on many hillslopes in the last two centuries.

Forests were also used for livestock grazing: beech and pine forests by sheep flocks in summer, and oak forests by sheep and cows in spring and autumn (Puigdefábregas and Balcells 1970). Farmers and communes occasionally sold the wood for use by the army and in public works when they needed money. For these reasons, the sizes of the forests varied according to the need for cultivated lands, grasslands, and money.

At present, forests represent 31% of the Central Spanish Pyrenees. They occupy most of the territory between 1400 and 1700 m on both the north- and south-facing slopes. Between 1700 and 2200 m they are located on the steepest slopes, as in the case of the *Pinus uncinata* forests, which resulted from human management of summer, subalpine grasslands. Under 1400 m, most of the forests have shady aspects, whereas the cultivated fields occupied sunny aspects. In some cases of generalized deforestation, the small forests were preserved to ensure the local population's supply of wood.

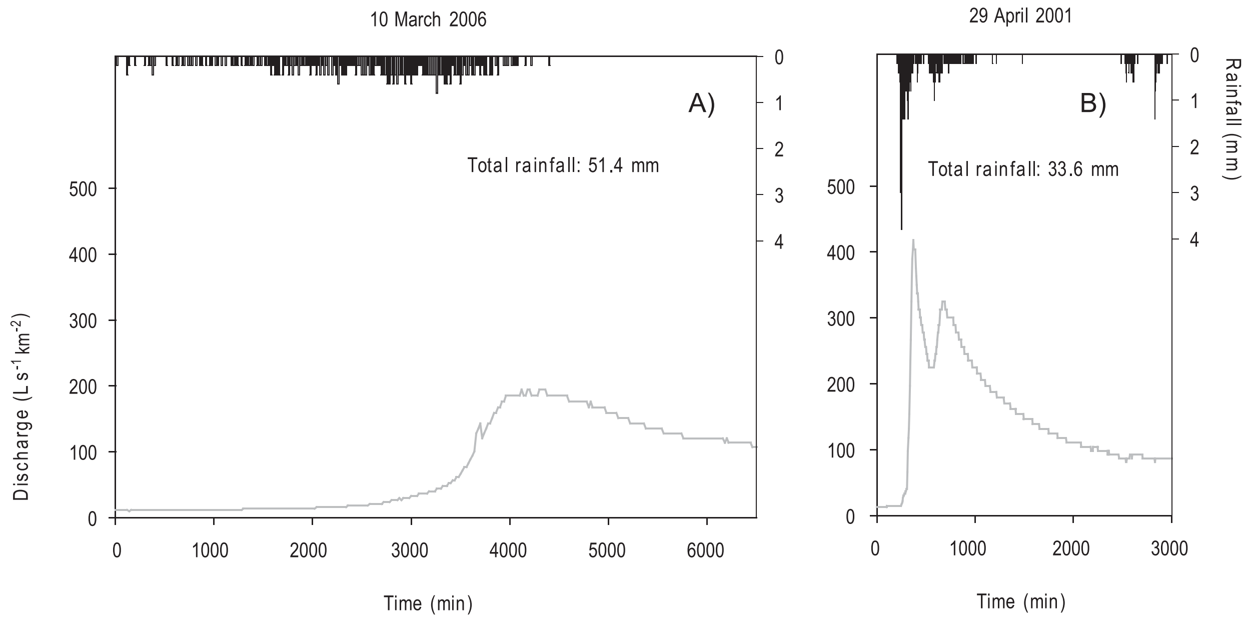
Equipment and methods

Monitoring began in the San Salvador catchment in 1999, though the data are not continuous until 2001. The equipment in the catchment provided information about meteorological variables, discharge, interception, and sediment concentrations, as well as about the water table height:

- 3 tipping bucket pluviometers located at 880, 1080 and 1270 m.
- A flume with an ultrasound sensor to measure the water height (Lundhal DCU-7110) from which discharge was obtained.
- An automatic water sampler (ISCO 3700, with 24 bottles) sampling flood waters to analyze the solute and suspended sediment concentration.
- A weather station (Campbell) located near the flume to measure air temperature, air humidity, wind velocity, solar radiation, and precipitation.
- 3 piezometers (Keller) to measure the depth to the water table.

FIGURE 2 Example of a dense forest in the San Salvador catchment. (Photo by María Pilar Serrano-Muela)

FIGURES 3A AND 3B Two examples of hydrographs for the San Salvador catchment.



All these instruments were connected to data loggers that record average values every 5 to 20 minutes, depending on the variables. Finally, 3 interception plots were installed under pine, beech tree, and oak cover, each with 25 pluviometers.

The data were used to identify individual rainfall–runoff events. For each event, rainfall and runoff volumes, runoff coefficient, and peak flow were determined. All these variables as well as water table series were analyzed to characterize the hydrological functioning of the catchment. The results obtained were compared to those from other experimental catchments located in the same area (Figure 1), which experience the same climate conditions but have different land cover: the Arnás catchment (286 ha), a human-disturbed environment, cultivated and grazed up to 40 years ago and now abandoned, with a relatively dense shrub cover, and the Araguás catchment (45 ha), which is affected by intense badland activity, with open shrubs and bare areas.

Hydrological behavior of the forested catchment

Most flood hydrographs for the San Salvador catchment are characterized by a moderate hydrological response to rainstorm events. Figure 3 shows two contrasting examples of hydrographs. The first (Figure 3A) is characterized by a long time lag in relation to the rainfall event, a slow reaction during the rising limb, an absence of a true peak flow, and a very slow recessing limb. However, the hydrographs are very different for some cases. For instance, the hydrograph in Figure 3B has a relatively intense peak flow in spring, with a fast flow increase, an acute peak flow, and a shorter time lag.

Figure 4 shows the evolution of the daily discharges throughout the hydrological year of 2005–2006 in San Salvador and the two other experimental catchments in the Flysch sector of the Central Pyrenees. Several features are significant:

- The rainfall events at the beginning of the hydrological year (autumn) produce no or only a very limited hydrological response in San Salvador, even though they are relatively intense. This should be attributed to the exhaustion of water reserves by the previous dry period, with an absence of rainstorms, and thus high water consumption by vegetation. For instance, a rainfall amount of 44 mm on 22 September 2006 did not cause a significant response in the San Salvador catchment, whereas it produced a peak flood of 4160 L s^{-1} km^{-2} in Araguás, and 260 L s^{-1} km^{-2} in Arnás. In fact, there was no increase in the discharge in the San Salvador catchment until the beginning of December, whereas in Arnás and Araguás discharge increases occurred from the beginning of November.
- Discharges in San Salvador were moderate in December and January, whereas noticeable discharge increases were observed in Arnás and Araguás.
- The only high flow period in San Salvador occurred in February and March and coincided with the long rainy period, with continuous rainfall from the mid-

dle of February. This was also an active period in Arnás and in Araguás.

- After April there were several rainstorm events that resulted in discharge increases in Araguás, very moderate responses in Arnás, and a long period with no discharge in San Salvador.
- There was no discharge increase in the San Salvador catchment at the end of the hydrological year, whereas Araguás recorded the biggest flood of the year.
- In 2005–2006 only 6 floods were identified in San Salvador, whereas there were 12 in Arnás and 44 in Araguás.

The particular behavior of the forest catchment can be explained in terms of the results shown in Figure 5, which shows daily data for precipitation, discharge, and water table level over a 6-month period. The discharge responses to rainfall events are very variable, in the range of 0 to 117 L s^{-1} km^{-2}, and are not related to the volume or intensity of rainfall. Instead, the water table level seems to have a large influence on the discharge: the discharge of the San Salvador catchment only increases in the event of rainfall when the soil is previously saturated, that is, when the water table is close to the soil surface at the start of the rainfall event. Otherwise, rainfall mainly serves to increase the water reserve within the soil, as in the case of the first significant rainfall event in October 2005. It is also interesting to note that the water table level undergoes intense fluctuations, with sharp declines once rainfall has ceased. This means that water flows quickly within the soil and the stony colluvium.

This may provide an explanation for the fact that the intensity and volume of rainfall events do not alone explain the hydrological response of the San Salvador catchment. Indeed, Figure 6 shows the relationships between maximum rainfall intensity in 5 minutes and peak flow for 37 rainfall events observed between 1999 and 2006, which have a very low, non-significant correlation (r=0.206). All the points are scattered and there is no trend. These results indicate that the functioning of the catchment is complex: in fact, different rainfall events produce similar responses in terms of peak flow, whereas similar rainfall events can result in very different discharges, demonstrating that peak flow value is not directly related to precipitation but instead to antecedent rainfall (Serrano-Muela et al 2005) and the height of the water table, ie it is directly associated to soil moisture conditions.

The annual runoff coefficients (2005–2006) were found to be 11%, 25%, and 69% for San Salvador, Arnás, and Araguás, respectively. These differences are clearly related to rainfall intercepted by the forest cover and to water consumption by plant cover during the vegetative period. The first interception data obtained for San Salvador between April and September 2006 indicate that, on average, pine, beech tree, and oak forests intercept 15, 22, and 18% of the rainfall, respectively. These figures will vary slightly over the long term, depending on the rainfall characteristics, but give a good idea of the hydrological differences between forested and non-forested environments.

FIGURE 4 Evolution of mean daily discharge (in the 2005–2006 hydrological year) in the San Salvador, Arnás, and Araguás catchments.

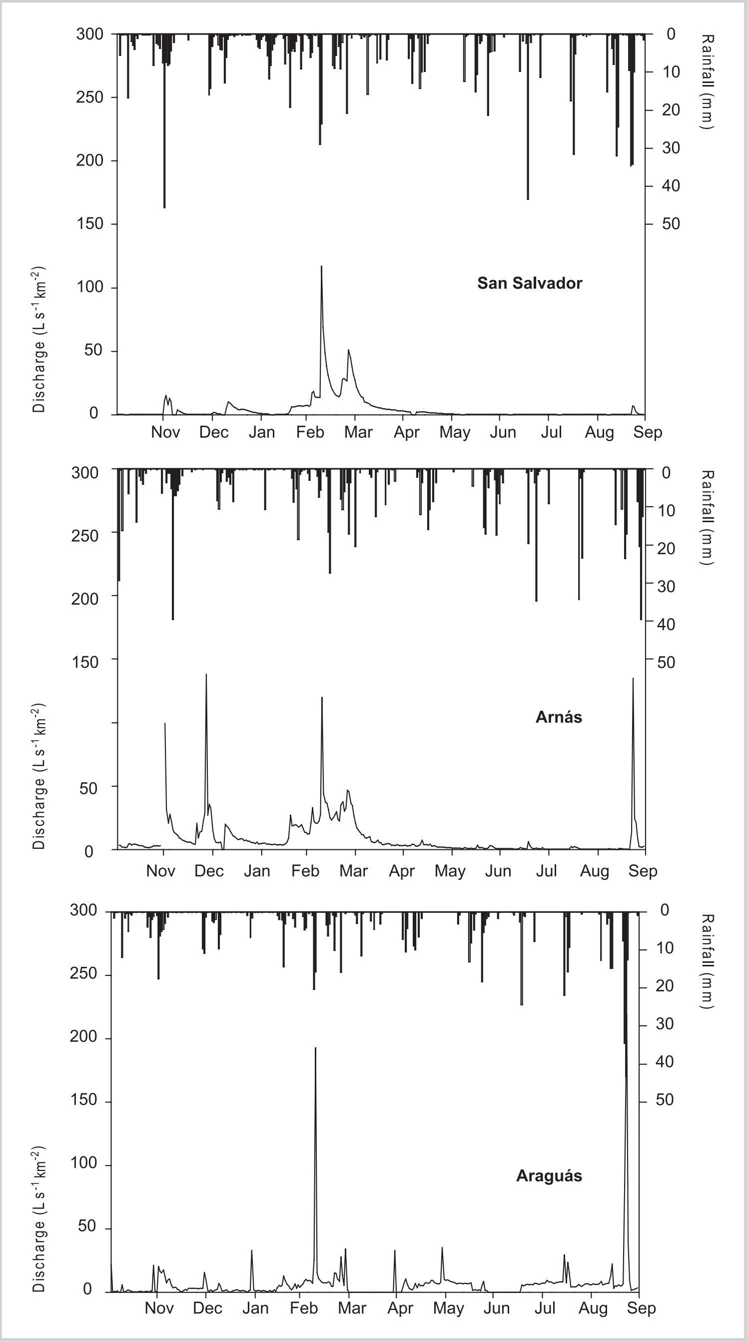


FIGURE 5 Precipitation, discharge, and water table level over a 6-month period (October 2005–April 2006) for the San Salvador catchment.

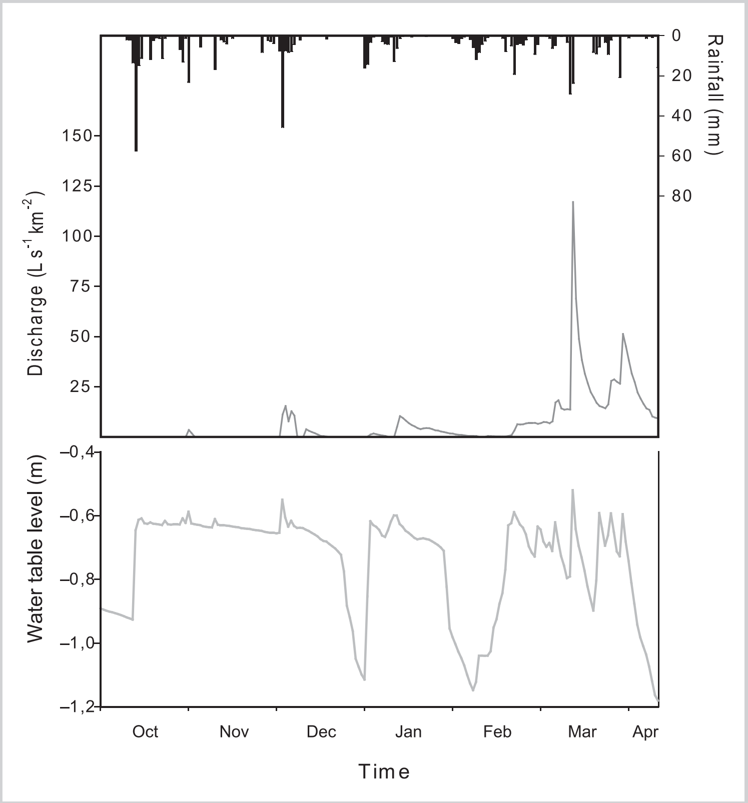
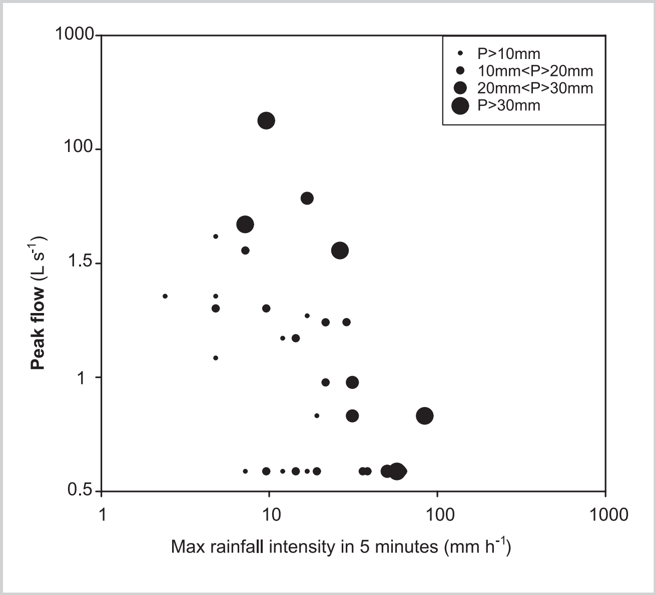


FIGURE 6 Relationships between maximum rainfall intensity and the corresponding peak flows for individual rainstorm events.



The hydrological behavior of a forested catchment also has important consequences for erosion and sediment transport. Most sediment exported from the San Salvador catchment was in the form of solutes (75% of the total), and the rest was suspended sediment. No true bedload was recorded during the monitoring period, except for fragments of calcite (travertine) precipitated on the bed of the ravine after being broken and carried during flood events. This suggests that most of the water circulates within the soil and colluvium, and that overland flow is almost residual.

Conclusions

The San Salvador catchment is an example of a non-disturbed forest environment with moderate hydrological behavior mainly controlled by evapotranspiration and sub-surface flow processes. Evapotranspiration (interception and water consumption by vegetation) is the likely explanation for the catchment's low runoff coefficient and the lower levels of its high and low flows. Subsurface flow is the main process explaining the discharge response of the catchment to a rainstorm event: significant streamflow generation is only active when the water table is close to the surface, thus supporting the idea that well-preserved forest soil tends to produce a storm hydrograph dominated by sub-surface flow processes.

Highest floods are most likely to occur in the San Salvador catchment in spring, at the end of the rainy, cold season, when the floods there can be of similar magnitude to those in deforested catchments; this result confirms that forests reduce the number of floods but do not significantly alter the hydrological effects of extreme rainfalls (White et al 1997). If the water table is far below the surface, then new rainfall is necessary for a flood, generally of low intensity, to occur. This is the reason why fewer floods occur in forest catchments than in the abandoned farmland and badland catchments in the area. It is also interesting to note that the intensity and even the volume of precipitation cannot be used to explain the characteristics of the hydrological response in the forest catchment.

Further, dense forest cover ensures the presence of a prevailing sub-surface flow, thus reducing soil erosion and delivery, as well as suspended sediment transport. This is the reason for the conservation of forest areas in traditional management systems, particularly on the steepest hillslopes. Deforestation in marginal, steep areas was only accepted during periods of strong demographic pressure, when the food supply (cereals) was supplemented with cultivation under shifting agriculture systems (Lasanta et al 2006). Several studies have shown that soil erosion and shallow landslides are related to deforestation (García-Ruiz and Valero-Garcés 1998; Lorente et al 2002) in both the subalpine and montane belts.

At present, depopulation and farmland abandonment encourage plant recolonization (Vicente-Serrano et al 2004); the shrubs and trees occupying the old fields contribute to a progressive moderation of the hydrological behavior of formerly deforested basins (García-Ruiz et al 2005). The consequences are reductions of the torrentiality of rivers and ravines and of lateral erosion, channel stabilization (Beguería et al 2006) at the local scale, and a decrease in streamflow and peak flows at the local and regional scales (Beguería et al 2003).

AUTHORS

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