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FLUVIAL HAZARDS IN A MOUNTAINOUS MEDITERRANEAN AREA

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Abstract: Intense rainfall events are a major trigger for flooding and landslides throughout regions with a Mediterranean climate. They create problems for settlements and infrastructures built across their paths. Changes in landuse have also been important in increasing or decreasing the intensity of the flood problem and the mobility of land surface materials, especially changes in the intensity of grazing on mountain pastures or historical deforestation and recent reforestation. This paper focuses on the rainfall thresholds that distinguish common events from rare, hazardous events. During the last few years, rainstorms of different intensities have occurred in the Central Spanish Pyrenees, including one of exceptional character. Large, historical debris flows have been studied, as well as the actual sediment transport in small experimental catchments. This study shows that during the most frequent events suspended sediment transport is the common geomorphic process. River bedload is mobilized in river channels several times per year, while small rock avalanches and channelized debris flows have a return period of at least 5 years. Hillslope debris flows are triggered by rainfall events with a 25-30 year return period. Reactivation of large, deep mass movements is linked to rainfalls of around 100 year return period (between 130 and 160 mm in 24 hours). Catastrophic geomorphic processes occur when precipitation exceeds a 100 year return period, as was the case of the Biescas campsite disaster. Geomorphic processes triggered by intense rainfall events have caused major damages and human disasters but the hazards have been reduced by the introduction of several control measures, including reforestation, the construction of check-dams, canalization of river segments and improved flood forecasting.

Key-words: Debris flows, Extreme events, Geomorphic thresholds, Rainfall intensity, Return periods, Sediment transport, Spanish Pyrenees.

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1. Introduction

Mediterranean areas are affected by intense rainstorms of random spatial distribution (Poesen and Hooke, 1997; López-Bermúdez and Romero-Díaz, 1992-93; Martín-Vide, 1985). These events are the main triggers for both flash flooding and landslides. Rainfalls exceeding 200 mm in 24 hours are relatively frequent and can occur almost every year in along the Spanish and Italian coasts. In general, the intensity of these rainstorms diminish inland since they are caused by very small, deep cyclones locally called "cold drops" that originate over the Mediterranean Sea. However, as hydrological and geomorphological knowledge of mountainous Mediterranean areas increases, the importance of low-frequency rainfall events is being confirmed (White and García-Ruiz, 1998), though their frequency is much lower than in the coastal areas.

1.1. Coping with Hydro-geomorphological Hazards

Human settlements are generally located outside of the flood zones. Those situated in the low-lying areas occupy small hills, terraces, glacial moraines or have been constructed on the outer limit of the alluvial plain. In some exceptional cases, however, villages can be found in partially active alluvial fans, as is the case of the villages of Anciles in the Ésera Valley and Sarvisé in the Ara Valley. Villages have also avoided the hillslopes affected by mass movements (landslides), even if they seem to be inactive. Gistaín in the Cinqueta Valley is an exception since it is located on the upper part of a large, very old earthflow. The area has been drained in order to control water infiltration and to prevent the triggering of new movements during the rainy season. These traditional adaptation methods were abandoned during the last two decades of the 20th century. At the same time, many tourist resorts were built on the alluvial plains (i.e. Linsoles, in the Ésera Valley and the new quarters in Aínsa, Cinca Valley), and even on alluvial fans (New Broto in the Ara Valley and Santiago in the Aragón Valley). Furthermore, the old drainage systems were abandoned, causing the reactivation of mass movements, as was the case in Gistaín during the November 1982 rainstorm (Martí-Bono and Puigdefábregas, 1983).

The increase of hydro-geomorphological hazards in the last decades led to the introduction of measures to reduce the intensity of the torrents and to mitigate their consequences. Thus, many deforested slopes have been reforested and this has notably affected the floods of less than a 10 year return period. The most active and dangerous ravines have been partially controlled with check-dams to reduce the transport of sediment to the alluvial fan and subsequently to the main river channels, thus stabilizing the channels and extending the useful life of the reservoirs. Most of these ravines are located in the flysch sector where large bedload transport has been reported (Lorente et al., 2000). Check-dams and other control works, especially construction of stable, concrete channels in the steepest sections, have contributed to the stabilization of the alluvial fans (Gómez-Villar, 1996). The frequency of flooding on the alluvial plains has also been partially reduced by canalizing some sections of the main rivers, especially along the Ésera, Cinca and Ara rivers, thus reducing locally the hazards of the most frequent floods. Furthermore, most of the Pyrenean rivers are monitored under an Automatic System of Hydrological Information (Spanish acronym: SAIH) maintained by the Ebro River Administration Office. This system provides on-line information on the river flows at the various gauging stations, as well as the reservoir levels, to improve the forecasting of large floods downstream.

2. Scope of this study

Most studies of pluviometric and hydrological events have been concerned with (1) the extreme events of rare occurrences and their impacts on the infrastructures and human settlements, and (2) rainfall characteristics (intensity, duration, atmospheric features of the storm, spatial distribution) and hydrological responses (time lag, concentration time, shape of the hydrograph, downstream changes in the shape of the flood wave). The geomorphic consequences of these events have been considered generally as a peripheral problem, and they have been taken for granted partly because of their common occurrences. However, this is an important geomorphological problem, since the study of events with different frequencies of recurrence would allow us to recognize the existence of thresholds in the triggering of different geomorphic processes.

Since 1986 the Department of Soil Erosion and Land-Use Changes of the Pyrenean Institute of Ecology has been studying the relationship between rainfall and geomorphic events, and the effects of land-use changes on these relations (García-Ruiz et al., 2001). Rainstorms of different intensities have occurred in the last few years, including one of exceptional nature (White et al., 1997; García-Ruiz et al., 1996). Additionally, some low-frequency geomorphic events have been investigated through studying the old debris-flows and lacustrine deposits in the Pyrenees.

The aims of this paper are:

i) to assess various pluviometric thresholds that give rise to the occurrence of different geomorphic processes;

ii) to identify the major geomorphic processes associated with rainfall events of various intensities;

iii) to assess the role of human activities in increasing the recurrence of geomorphic processes for rainfall of particular intensities;

iv) to specify the main measures adopted to mitigate the hydrological and geomorphological impacts of intense rainstorms.

3. Study Area

3.1. Geology and Topography

The Spanish Pyrenees are formed by intense tectonic deformations that caused thrusting and folding of the sedimentary beds. They are composed of several west-east parallel geological units (Fig.1):

i) the Paleozoic Pyrenees, made up mainly of shales and limestones, as well as granitic intrusions, with peaks rising above 3,000 m a.s.l.;

ii) the Inner Ranges, composed of Cretaceous and Paleocene sediments, mostly limestones, sandstones and marly limestones, with relief that is dominated by high cliffs, intense karstification, glacial cirques, active avalanche paths and screes;

iii) the Eocene flysch sector, with a uniform relief dominated by rounded divides, was occupied by major glaciers during the last glaciation to produce lateral and terminal moraine complexes. In the wider valleys (Gállego, Esera, Aragón) there are several partially active alluvial fans.

iv) the Inner Depression developed on Eocene marls, forming a wide valley with terraces and glacial deposits;

v) the Pre-Pyrenees, including the External Ranges, with Cretaceous and Eocene sandstones and limestones, and Oligocene molasses, separated by a thrust system from the Ebro Depression that is mostly filled with Tertiary continental deposits.

3.2. Climate characteristics

The Pyrenees belong to a humid environment which contrasts strongly with the drylands located immediately to the south. Above 1000 m a.s.l., mean annual precipitation exceeds 1000 mm, reaching 1800 mm around 2000 m and exceeding 2500 mm on the highest peaks (Rijckborst, 1967). Several kilometres to the south, in the centre of the Ebro Depression, mean annual rainfall is between 300 and 350 mm.

The Pyrenees are subject to Atlantic and Mediterranean influences that produce strong north-south and east-west temperature and precipitation gradients. From west to east the humid Atlantic influence decreases and the Mediterranean influence (drier but with more intense rains in autumn) increases. The 0ºC isotherm during the cold season is located between 1600 and 1700 m, and above this level, the snow persists from at least December to April (García Ruiz et al., 1986).

Autumn and spring are the wettest seasons, though in the westernmost part of the Pyrenees precipitation mainly falls in the winter. Summer is usually dry but with occasional rainstorms, especially in the central-eastern part of the Pyrenees.

2.3. Seasonality and spatiality of the most intense rainstorms

Annual maximum values of daily precipitations tend to concentrate between August and November, especially in October (17.2% of the total) and November (16.5%). Autumn (September, October and November) represents 45.1% of all of the annual maxima (García-Ruiz et al., 2000a). This result is consistent with the heavy rainstorms caused by the hot and wet air masses coming from the Mediterranean Sea. Records of very intense rainfall are also relatively frequent in August (9.0%), as was the case for the Biescas campsite disaster (August, 7, 1996), Ribagorzana valley floods (August, 2-3, 1963) and Basque Country floods (August, 25-27, 1983) which caused considerable damages and even life losses.

The calculated return periods of high intensity rainfall can differ greatly among sites that are close to each other and this casts uncertainty on the reliability of the return periods estimated for precipitation over 100 mm (White et al., 1997; García-Ruiz et al., 2000a). For example, within relatively short distances, the return period for a precipitation of 150 mm can range between less than 20 years and almost 60,000 years

(Table 1), confirming the spatial irregularity of extreme pluviometric events. Recent studies demonstrate that the areas most directly affected by the Atlantic or Mediterranean influences (the northwestern and the southeastern part of the Pyrenees, respectively) have recorded the highest daily precipitation, while the Inner Depression records the lowest values due to its relative isolation from these influences (Beguería and Lorente, 1999).

4. Methods

The methods used to analyze the hydro-geomorphic effects of pluviometric and hydrological events include:

i) analysis of geomorphic maps at a 1: 50,000 scale to assess the spatial distribution of geomorphic processes (González et al., 1995);

ii) statistical analysis of precipitation to determine the return periods for different pluviometric events and their spatial variability;

iii) paleolimnology using samples taken from sediments accumulated during the Holocene to enable the identification and dating of ancient events of major geomorphic consequences;

iv) field study of the geomorphic effects of pluviometric and hydrological events of different intensity (from less than 1-year return period to more than 100-year return period), including discharge estimation and identification of the major geomorphic processes on the hillslopes and in the fluvial channels;

v) study and dating of deposits attributed to large debris flows that occurred in historical times;

vi) analysis of the information collected from experimental catchments located in high (Izas catchment) and middle mountains (Arnás and San Salvador catchments) to provide water and sediment discharge data related to low to medium intensity events (Alvera and García-Ruiz, 2000; Arnáez et al., 1998).

5. Geomorphic Consequences of Rainfall and Hydrological Events

Based on recent and historical events and rainfall data from two weather stations located at different elevations (Fig. 2), the events are classified into five groups:

i) very frequent events corresponding to less than 1 year return period;
ii) frequent events that occur at least once in every 5 years;
iii) rare events corresponding to a 25 year return period;
iv) very rare events with a return period of 100 years; and
v) exceptional events with a return period that greatly exceeds 100 years.

For each group of events the following characteristics are examined: (1) precipitation and/or hydrological features, (2) sediment transport features, and (3) the most outstanding geomorphic processes on the slopes and in the channels.

5.1. Very Frequent Events (Return Period: 1 year or less)

Events of high frequency produce small geomorphic changes. The small quantity (and almost always of low intensity) of rainfall and the accompanying low peakflow explain the absence of major erosional or mass movement activities.

5.1.1. Precipitation and Hydrology

The most frequent events, occurring with a 1 year return period, record up to 50 mm of precipitation in 24 hours, though they can reach 60-65 mm above 1200 m a.s.l. Rainfall exhibits a relatively minor spatial variability, closely linked to relief heterogeneity. These events are generally caused by the passage of polar fronts and they affect a large territory. Only short but intense summer rainstorms show large spatial variability and affects limited areas.

Hydrological response depends mainly on the rainfall intensity, but antecedent soil moisture is also very important. Thus, the low winter or spring precipitation (i.e. 10 mm in 24 hours) generates low peak flows, but with a high soil moisture content in the summer or the beginning of autumn, peak flows can exceed 25-30 mm. This accounts for the low correlation between precipitation and peak flow in small catchments (Fig. 3). For the main rivers, their discharge rises between 3 to 5 times above the average, at least in each year.

5.1.2. Sediment Transport

As expected, large quantities of suspended sediment are recorded as discharge increases, though their correlation is lower than expected in small catchments (Fig.3). Figure 4 shows two examples of the rainfall, streamflow and suspended sediment concentration of the two events in the Arnás catchment. In general, the peak suspended sediment concentration precedes the peak flow (Fig. 4 a). Figure 4b shows that a second peak flow during a long rainstorm event is accompanied by a lower sediment peak due to an exhaustion of sediment supply. In any case, during these very frequent events most of the sediment transported by the rivers is mobilized from the channels and their adjacent zones.

In catchments smaller than 10 km^2 bedload transport starts at over 200 l s^{-1}km^{-2}, occurring around 5-6 times per year, as has been recorded in the Izas and Arnás catchments (García-Ruiz and Alvera, 1998; Arnáez et al., 1998). Nevertheless, it is important to note that both suspended sediment and bedload are mobilized only from the deforested catchments. If the hillslopes are completely forest covered, even the most frequent rainstorms and their accompanying high discharges will not provoke any significant transport of sediments except solutes.

5.1.3. Hillslope and Channel Processes

Very little happens geomorphologically during the most frequent events. Braided rivers show negligible changes and no lateral erosion is detected in channels except those belonging to catchments smaller than 5 km^2. Near the channels sheet wash erosion occurs on the lowest parts of the convex hillslopes.

5.2. Frequent Events (Return Period: 5 years)

5.2.1. Precipitation and Hydrology

Events of a 5-year return period deposit around 70 mm of rain in 24 hours at 800 m a.s.l. and around 80 mm above 1100 m, with relief causing much of the spatial variability. All alluvial plains become completely flooded and most hillslopes produce runoff to the rivers, as happened during the storm event of 22 May, 1990 (Ruiz-Flaño and García-Ruiz, 1990).

5.2.2. Sediment Transport

Main rivers transport large quantities of suspended sediment derived from all parts of the basin, though bedload is mobilized only locally. Sporadic hyperconcentrated flows can develop, creating debris flows that produce lobate accumulations in segments with gentle gradients. Bedload accounts for the most important part of the sediment balance in small catchments, supplying coarse materials to the main channels to be transported subsequently during the more infrequent events. Taking the January 1996 rainstorm event in the Arnás catchment as an example, bedload represented 70 % of the sediment output, while 16 % was suspended sediment and 14 % was in solute load (González et al., 1997).

5.2.3. Hillslope and Channel Processes

The frequent events cause moderate re-organization of the channels and bars in braided rivers, which are also subject to moderate lateral erosion. Occasional channelized debris flows occur in the headwater zones of the ravines, as in the Ijuez rivers or in tributaries of the Aurín river. In some rare cases, small rock avalanches along structural faults may occur, such as that of Nueno, on the road between Zaragoza and France.

5.3. Rare Events (Return Period: 25-30 years)

The so-called rare events occur at least once every 25-30 years and are related to a significant increase in precipitation. Two events have been studied, one affecting several central-western valleys of the Spanish Pyrenees (November, 1982) and the other the Izas experimental catchment (October, 1987).

5.3.1. Precipitation and Hydrology

Rainfall between 100 and 120 mm in 24 hours are recorded diromg rare evemts. Sjpwomg a moderate spatial variability related to the relief heterogeneity. Figure 5 shows the relationships between precipitation and altitude of different weather stations of the Spanish Pyrenees during the November, 1982 storm event. Very frequently, rainfall can last more than 24 hours and even several days, reaching a total of more than 200 or 300 mm. The event included several rainfall peaks of high intensity separated by less intense intervals, and this generated hydrographs that have multiple peaks. The alluvial plains are completely flooded, affecting infrastructures and even buildings. Flooding also extended to the active zones of the alluvial fans.

5.3.2. Sediment Transport

Large quantities of sediment are conveyed in all rivers irrespective of their size, with an increasing importance of bedload. For example, the October 1987 rainstorm event in the Izas catchment yielded a total sediment output of 19,750 kg, of which 17,000 kg were bedload, 2,000 kg solutes and 750 kg suspended sediment (Díez et al., 1988). Data from small catchments (Izas) reveal that total sediment transport can represent as much as all the sediment mobilized in 10 years (García-Ruiz and Alvera, 1998; Alvera and García-Ruiz, 2000). After that, many channels can remain exhausted of sediment supply for several years. Figure 6 shows bedload transport evolution from 1987, confirming that bedload transport became unimportant after the October 1987 storm event, in spite of the subsequent occurrence of intense rainstorms. In fact, a second rainstorm a week later was only able to remove 475 kg of bedload, even though it had similar peak flow.

5.3.3 Hillslope and Channel Processes

The most important geomorphic consequence is the triggering of debris flows, mainly affecting the old cultivated or grazed areas on steep slopes. Studies on debris flow distribution using Geographic Information System demonstrate that they are mainly located on sunny slopes, between 800 and 1400 m a.s.l. in areas with shrubs and open, degraded submediterranean forests (González et al., 1995; García-Ruiz and Puigdefábregas, 1982).

Above the present upper forest limit some small planar slides (≅ 5 m of scar diameter) can develop occasionally. These slides, sometimes in the form of slumps, occur close to the river channels (due to lateral undercutting) and roads. Braided channels are affected by intense erosion, increasing the bedload transport and contributing to the development of debris flows and hyperconcentrated flows. Some river stretches, mainly in the headwaters, appear to be infilled by enormous volumes of coarse, non-sorted sediment (Martínez-Castroviejo and García-Ruiz, 1990). Most of the alluvial plains undergo intense changes in sedimentary structures and vegetation while large alluvial fans show small morphological changes due to the accumulation of debris flow at their apexes.

5.4. Very Rare Events (return period: 100 years)

In the central-eastern valleys of the Spanish Pyrenees, the November 1982 rainstorm corresponded to a recurrence of around 100 years, or perhaps more in some localized areas (Martí-Bono and Puigdefábregas, 1983).

5.4.1. Precipitation and Hydrology

Precipitation corresponding to a 100-years return period is around 130 and 160 mm in 24 hours in most parts of the Pyrenees, reaching larger magnitudes above 1500 m a.s.l. The November 1982 rainstorm, originated from a Mediterranean low-pressure cell that first affected the Mediterranean coast and then the central-eastern Pyrenees where the rugged topography favoured the intensification of the storms in two days. Some valleys recorded more than 400 mm (Cinqueta valley) and some areas above 2000 m a.s.l. recorded over 500 mm. The Góriz weather station, at 2262 m, received more than 600 mm in 24 hours. Towards the west the storm became less intense, producing rainfalls of around 25-year return period (see 4.3) and only around 5-year return period in the western Pyrenees (Martí-Bono and Puigdefábregas, 1983).

This group of events tends to show relatively large spatial variability, being strongly influenced by the topography. In general, discharge reaches more than 3,000 l s^{-1} km^{-2} in basins of more than 1,000 km^2, but little information is available on the hydrological impacts in the small experimental catchments.

5.4.2. Sediment Transport

These very rare events cause the accumulation of large quantities of coarse sediment in the river channels, forming debris flows. Morainic blocks collapse into the secondary ravines and are carried to the river channels. No information exists on the proportion of bedload in the sediment balance.

5.4.3. Hillslope and Channel Processes

The November 1982 rainstorm in the central-eastern Pyrenees produced very intense geomorphic effects both in the channels and on the hillslopes. The following consequences were particularly notable:

i) lateral undermining of the screes located in the valley bottoms and destruction of small road stretches (Cinqueta valley), due to the narrowness of the valleys and the steep gradients of more than 3%,

ii) general mobilization of sediment in semi-active and active alluvial fans (Remáscaro fan, in the Esera valley; Jou-La Guingueta fan, in the Noguera Pallaresa valley), with the arrival of large volumes of morainic materials (Bru et al., 1984), and the reactivation of some seemingly inactive mountain sites,

iii) triggering a number of mass movements of different sizes (slides, slumps, debris flows), especially in agricultural, non-forested areas (Clotet and Gallart, 1984; Clotet et al., 1989),

iv) reactivation of large, deep mass movements. Thus, the Gistain slide developed on the black Paleozoic slates, opening up large, tranverse cracks at the backwall, measuring 100-150 m in length and with a step height of 0.50 m. At the concave zones of this slide, debris flows were triggered, starting from the borders of old, abandoned cultivated terraces.

v) development of several planar slides above the present upper forest limit.

5.5. Exceptional Events (Return Period: unknown)

Two examples of the exceptional events have been studied in the Spanish Pyrenees, one being recent and the other was triggered at least twice in historical times. The first one was responsible for the Biescas disaster that occurred on August 7, 1996 (García-Ruiz et al., 1996; White et al., 1997), destroying an entire campsite situated in the path of the torrent and killing 87 people. The second is the San Adrián de Sasave debris flow that buried a Middle Age monastery in the 13th and 18th centuries (Martí-Bono et al., 1997).

The recurrence period of exceptional events is unknown, though in any case more than a 100-year return period. Previous studies demonstrated that the return periods of very intense precipitation events cannot be established reliably and the margin of error is so large that the estimates are rendered meaningless (García-Ruiz et al., 2000b).

5.5.1. Precipitation and Hydrology

Rainfall recorded during exceptional events reached around 200 mm in 1 hour, or more than 500 mm in 24 hours. Recently (May, 6, 1999) a rainfall of 70 mm in 10 minutes was recorded in a weather station of the Aisa Valley (Lastiesas), but its impacts were limited due to its short duration.

The area affected by the most intense precipitation is usually very small (only a few km^2, around 4 km^2 in the case of the Biescas disaster), showing an extreme spatial variability (erratic spatial distribution). No relationship could be obtained between various characteristics of the relief and the distribution of precipitation exceeding 200 mm in 24 hours (García-Ruiz et al., 2000a). In general, these rainstorms are caused by the arrival of cold air masses at high altitudes, overriding hot and wet air masses at the lower atmosophere.

From a hydrological point of view, the consequence is the development of catastrophic floods, usually affecting small catchments. In the case of the Biescas campsite disaster, peak flow for a catchment of 18 km^2 reached between 400 and 600 $m^3\ s^{-1}$ according to different authors (Benito et al., 1998; White et al., 1997; Alcoverro et al., 1999). During the recent intense rainstorm of the Aisa Valley, a 78 ha catchment produced a flood of 27 $m^3\ s^{-1}$ (García-Ruiz et al., 2000 b).

5.5.2. Sediment Transport

The events studied in the Spanish Pyrenees demonstrate that, under extreme conditions, the sediment is transported by large hyperconcentrated flows (Gutierrez-Santolaya, 1998) or debris flows that can occupy the whole valley floor. During the Biescas campsite disaster, at least 122,000 to 136,000 tonnes were carried to the alluvial fan, including large morainic blocks (García-Ruiz et al., 1996).

5.5.3. Slope and Channel Processes

Exceptional events produce severe changes in fluvial channels and on the hillslopes, including:

i) the destruction of infrastructures of different sizes, including check-dams, roads and bridges (e.g. almost thirty check-dams failed along the final stretch of the Arás river during the Biescas disaster, thus increasing the volume of sediment transported),

ii) strong lateral and vertical erosion in ravines, especially when they cross lateral moraines, iii). development of large, channelized debris flows, like that of the San Adrian de Sasave monastery. Two different debris flows have been dated, one during the 13th century and the other in the second half of the 18th century, leaving the church almost completely buried. This phenomenon is also worsened by deforestation that has affected the catchment since the 11th century, increasing sediment yield and availability.

iv) the triggering of large, deep mass movements (especially in the slates and the flysch sector) which is little known until recently. During the Biescas disaster, the intensity of rain was so high and its duration so short that infiltration was very limited and this reduced the hazard of mass movement. In other cases when rainfall is prolonged, deep mass movements are possible, though they are not active at present. Some of them were developed after the upper forest level was deforested since the 12 century, thus intensifying the erosional processes (Montserrat, 1992), but others are very much older.

6. Conclusions

The Pyrenees experience high intensity rainfalls and floods, especially in the central-eastern part, due to the passage of small Mediterranean cyclones. The autumn is the most dangerous season, though some of the most intense rainstorms also occur in August (e.g. that causing the Biescas campsite disaster).

It is well known that there is a general increase in geomorphic activities associated with the pluviometric events of increasing return periods. This is the case for suspended sediment and bedload transport, as well as for channel erosion and mass movements, though their relationship with rainfall and streamflow is non-linear. Two factors are of importance.

(1) *The rainfall thresholds that trigger new sets of geomorphic processes*:

As the intensity and amount of rainfall increase, so does the magnitude of certain geomorphic process, until a level of rainfall is exceeded to activate a new set of processes, not just an intensification of the previous ones. For example, suspended sediment concentration has usually a maximum level of "saturation" beyond which even if rainfall continues or the event intensity increases, an increase in river discharge does not necessarily raise the suspended sediment concentration. On the other hand, such flow conditions will initiate bedload transport. Further rainfall increase will generate hyperconcentrated flows and hillslope debris flows. In extreme events alluvial fans are remobilized and cause catastrophic channelized debris flows together with deep mass movements on hillslopes.

In the case of the Spanish Pyrenees, suspended sediment transport is the usual geomorphic process during the most frequent events that have a return period of 1 year or less. Bedload is moved several times per year. Small channelized debris flows and small rock avalanches on steep slopes need a return period of at least 5 years. In the absence of a dense forest cover, hillslope debris flows appear with rainfalls corresponding to a 25-30 year return period; slides of around 5 to 15 m in diameter also occur close to the river channels due to lateral undercutting. Reactivation of large, deep mass movements is linked to rainfalls of around a 100 year return period, as well as the development of planar slides above the upper forest limit and the remobilization of sediment in alluvial fans. Beyond this threshold, catastrophic geomorphic processes occur, including the destruction of infrastructures, the development of large, channelized debris flows and the triggering of deep mass movements.

(2) *Alteration of the vegetation cover by human activities*:

The occurrence of debris flows coinciding with a 25 year return period rainfall event is clearly pre-conditioned by overgrazing or cultivation on steep slopes. Exceptional rainfall is required to provoke widespread debris flows on well-forested slopes. The development of the San Adrián de Sasave channelized debris flows in the 13th and 18th centuries was favoured by extensive deforestation of the catchment, increasing erosion and sediment yield. Today, when the entire catchment is again forest covered, it is impossible to imagine a similar geomorphic process.

In general, processes linked to rainfall events with return periods less than 25 years can carry a lot of heterogeneous sediments, but the effects on the landscape are relatively minor. On the other hand, the less frequent events (more than a 100 year return period) can introduce very important modification of the landscape, but since they affect a very localized area, they have a limited regional importance.

Construction in areas prone to geomorphic hazards, the abandonment of old drainage system and deforestation have increased the severity of geomorphological events, with serious impacts on the environment and on human activities. Mitigation measures have been introduced, including the reforestation of hillslopes and the construction of check-dams across dangerous ravines. Monitoring the rivers in the Pyrenees makes real-time information available from many gauging stations, and this improves the forecasting and warning of flood occurrences.

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Table 1. Return periods for various amounts of precipitation in the Central Pyrenees

Site	Altitude m a.s.l.	Record (years)	Return period for		
			50 mm	100 mm	150 mm
Aragüés	970	24	1.5	18	335
Biescas	890	21	1.5	9	91
Hecho	833	21	1.1	11	213
Jaca	818	21	1.8	104	8050
Lasarra	1450	19	1.0	3	21
Sabiñánigo	790	28	2.2	37	805
Sin	1218	21	1.7	2	5
Graus	498	24	2.8	374	59918

FIGURE CAPTIONS

Fig. 1. Study area. 1: Lastiesas. 2: San Salvador experimental catchment. 3: Arnás experimental catchment. 4: San Adrián de Sasave Monastery. 5: Izas experimental catchment. 6: Góriz. 7: Gistaín. 8: Remáscaro alluvial fan. 9: Jou-La Guingueta alluvial fan. 10: Nueno.

Fig. 2. Maximum precipitation in 24 hours, corresponding to different return periods at Jaca (820 m a.s.l.) and Yésero (1132 m a.s.l.).

Fig. 3. Relationship between precipitation and discharge in the Arnás experimental catchment.

Fig. 4. Discharge and suspended sediment concentration during two rainstorm events in the Arnás experimental catchment.

Fig. 5. Relationships between precipitation and altitude in the Central Spanish Pyrenees during the November 1982 rainstorm event (source: Martí-Bono and Puigdefábregas, 1983).

Fig. 6. Bedload transport evolution in the Izas experimental catchment (1987-1998).