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Slushflows at El Port del Comte, northeast Spain

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ABSTRACT. Slushflows were first recorded in the Iberian Peninsula on 18 December 1997. Three slushflows were released at the ski resort of El Port del Comte, in the Catalan Pyrenees, northeast Spain, during intense rainfall. Two of the slushflows originated on the pistes, and the third affected another piste. Three ski lifts were damaged. This paper analyzes the hydrogeological characteristics of the massif, the geomorphic features of the terrain and the meteorological and snowpack conditions that caused the release of the slushflows. Man's role in triggering the slushflows by compacting snow on the pistes is also considered. Drainage control for reducing the hazard is outlined, taking into consideration the low frequency of the phenomenon.

INTRODUCTION

Slushflows, or rapid mass movements of water-saturated snow (Hestnes and others, 1994), are characteristic of high latitudes, though they can occur wherever snow cover is seasonal (Hestnes, 1985; Onesti and Hestnes, 1989; Hestnes, 1998). Slushflows had never been reported in the Iberian Peninsula until they occurred at the ski resort of El Port del Comte (Fig. 1), located in the southernmost part of the Catalan Pyrenees (42°10′ N, 5°13′ E). The altitude of the El Port del Comte massif ranges from 1800 to 2380 m a.s.l. The snowfalls are, in general, lighter than in the rest of the Pyrenees.

Between the evening of 17 December and the morning of 18 December 1997, after 2 days of intense rainfall, three slushflows were released within the ski resort. They affected three pistes and damaged three ski lifts.

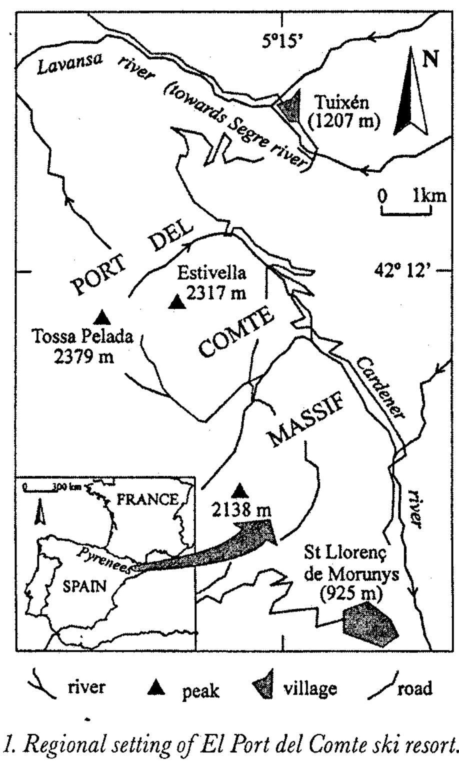

Fig. 1. Regional setting of El Port del Comte ski resort.

The release, downslope propagation and runout of slushflows are closely related to the rate and duration of water supply, snowpack properties and geomorphic factors (Hestnes, 1998). This paper analyzes the El Port del Comte slushflow release mechanisms.

THE SLUSHFLOWS

The main characteristics of the released slushflows are summarised in Table 1. The slushflow paths are mapped in Figure 2 and their profiles are shown in Figure 3. Slushflow 2 comprises two slushflows that converged in the track zone after being released from two separate starting zones.

Slushflow 1 had the following characteristics. Its starting zone was located at the lower end of a gentle concavity of the slope. It was released on a ski piste, in compacted snow with low porosity. It started as a small slab avalanche. A sharp scar and a number of snow blocks with fragile fractures just above the slab release were readily identifiable. At the base of the approximately 0.4 m snowpack a 0.15 m grey layer of

Table 1. Main characteristics of the slushflows (see Fig. 2) and the terrain

	Slushflow No.			
	1	2		3
Starting-zone orientation	NNE	NE	N	ENE
Starting-zone altitude (m)	1970	2190	2190	2280
Release associated with	piste	piste	spring	spring
Slope				
Starting zone	18.5°	16°	23°	9°
Track zone	10.5°	10.5°		16°
Runout zone	5.5°	10.5°		1.5°
Vertical drop (m)	230	290		330
Length (m)	1440	945		1328
Damage	Ski lift	Two ski lifts		–

Note: N, north; E, east.

Fig. 2. Simplified geological map of El Port del Comte ski resort area. Slushflows are mapped in black; their numbers correspond to those in Table 1 and in the text.

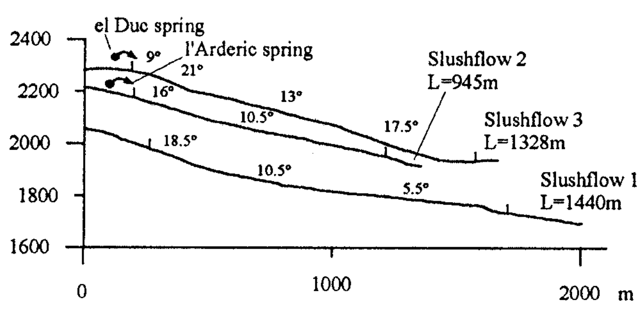

Fig. 3. Topographic profiles of the slushflow paths. L is the length of the flows. Starting locations and runouts are shown by vertical lines. Starting zones of slushflows 2 and 3 were associated with sporadic springs. Slope angles represent the different sections of the paths, and do not correspond to the mean inclinations of the starting zones, tracks and runout zones.

saturated snow was recognised several hours after the release (Fig. 4). At the soil–snowpack interface an ice crust thicker than 20 mm formed, probably after release and the end of the storm, when temperatures dropped below 0°. Its characteristics indicate a copious circulation of water over frozen and/or oversaturated soil. There were snowballs about 50 m below the starting zone. This is consistent with the observations of Hestnes and others (1994) and Hestnes (1998), who affirm that slushflows may also start as wet slab avalanches and, in such cases, liquefaction may be instantaneous. Slushflows 2 and 3 were released from springs.

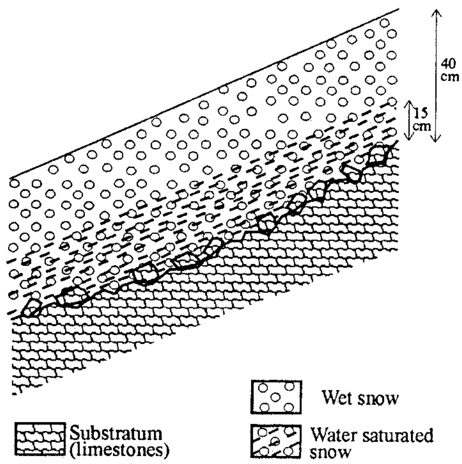

Fig. 4. Schematic lateral view of the scar: 0.4 m of wet snow with a 0.15 m high water-table a few hours after the release of the slushflows.

In each case, the dense flux of snow and water adapted perfectly to the topography and was able to transport single rocks with diameters of several cm to a few tens of cm, yet did not affect the substratum. The impact pressures of the slushflows were high enough to destroy three ski lifts.

METEOROLOGICAL CONDITIONS

At the onset of precipitation, approximately 0.5 m of homogeneous snow covered the ski area. In the two slushflow starting zones located in the pistes the snow was compacted.

The precipitation began with a snowfall that immediately turned into an intense rainfall. As shown in Table 2, the precipitation that fell on these 2 days was twice the total mean December precipitation and equivalent to the mean winter precipitation (Clavero Paricio and others, 1996). This extraordinary amount of precipitation was the main reason for the release of the slushflows.

The seasonal precipitation regime in this region reaches a maximum in spring, declines in summer and autumn and

Table 2. Liquid precipitation before the triggering of the slushflows and mean precipitation† at El Port del Comte, in mm*

Precipitation 16–18 December 1997	> 140
Annual mean precipitation	850–950
December mean precipitation	60–70
Winter mean precipitation	140–160

* Data from the Instituto Nacional de Meteorologiá meteorological station for the ski resort at 1650 m a.s.l.

† Data from Clavero Paricio and others (1996), calculated from a data series shorter than 30 years.

reaches a minimum in winter (Clavero Paricio and others, 1996). The most important precipitation usually occurs after the melting of the snow cover, so the high amount of rainfall on 16–18 December 1997 was unusual.

Temperatures had fallen below zero before the precipitation event. A minimum temperature of −6°C was registered on the morning of 16 December at 1650 m a.s.l. Basal refreezing of the water probably significantly reduced the permeabilty of the highly porous soil surface locally.

HYDROGEOLOGICAL CONTEXT

The ski resort is located on a Cretaceous calcareous massif (Pyrenees upper thrust sheets; Solé-Sugrañes, 1973; Vergés, 1993). The karstification is intense, with well-developed exokarstic (dolines) and endokarstic (caves) forms. The Cardener and the Segre rivers (Fig. 1) constitute the general hydrological gradient base level of the massif (Coll and Llobet, 1983).

In the ski resort area there are interstratified layers. The lower one is constituted by impermeable marls. This layer favours the formation of perched or epikarstic aquifers. In the vadose zone these act as storage units. During periods of high aquifer recharge they operate as sporadic springs, just above this stratigraphic level (Figs 2 and 5).

The starting zones of two slushflows were directly associated with two such sporadic springs, the l'Arderic spring and the el Duc spring (Table 1; Figs 2, 3 and 5). The springs were active at this time because of the intense rainfall.

DISCUSSION AND CONCLUSIONS

The most likely cause of slushflows is the reduction in cohesion due to the presence of water and the substantial reduction in the friction component of snow strength due to the hydrostatic pressure resulting from the presence of standing water in the snowpack (McClung and Schaerer, 1993). Thus, the factor which determines the release is the hydraulics of the water table (Gude and Scherer, 1998; Scherer and others, 1998). In El Port del Comte the exceptional rainfall infiltrated the snowpack and the underlying aquifers. Locally, this generated an unusually high water table at the base of the snow cover; part of the rainfall remained in the snowpack and part infiltrated into the underlying aquifer. Some hours later water from the aquifer infiltrated into the snowpack as discussed below.

The fluctuation of the water level in the snowpack is a significant indicator of stability. A sharp rise in water level in drainage courses is critical to slushflow release (Hestnes, 1998). The water supply generated by the recharge of the aquifers, and the fact that the sporadic springs became operational probably some hours after the saturation of the base of the snow cover, led to a sudden rise in the local water table. As a result, the slushflows, originating in the springs, were released.

In Norway, slopes exposed to wind during frontal passages are normally the most susceptible to slushflows during winter (Hestnes and others, 1994). The starting zones of the El Port del Comte slushflows in December 1997 were all oriented to the first quadrant (northeast). This was not consistent with the southeasterly wind direction during the storm, indicating that the meteorological conditions necessary for slushflows are different to those in Norway.

The slope concavity and low hydraulic conductivity of

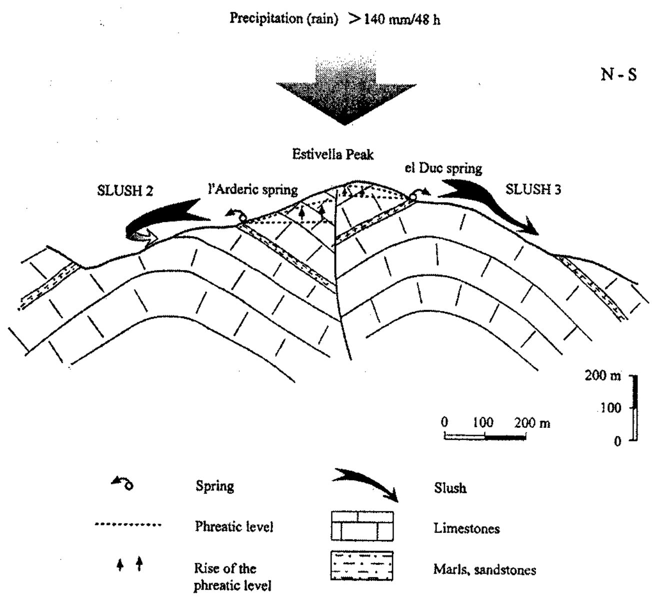

Fig. 5. Hydrogeological section including Estivella peak and l'Arderic and el Duc springs. Slushflows 2 and 3 originated in these springs. The perched aquifers feeding the springs are limited at the base by the marl layer. The phreatic-level rise produced by infiltration of rainfall is shown by small arrows and dashed lines. The important phreatic-level gradient generated implies a considerable surge through the springs.

the frozen soil might therefore explain the concentration of water needed to release slushflow 1. All of the slushflows were released and propagated along zones whose morphology favours the concentration of water (Fig. 2).

The release, downslope propagation and runout of the El Port del Comte slushflows were closely related to the water supply, snowpack properties and geomorphic factors. The main difference from Arctic slushflow release is the control of the water input into the snowpack. In Arctic regions this is mainly related to meteorology: frontal passages in winter (Norway) and the thaw season. In El Port del Comte the means of control is the hydrogeologic karstic structure inherent in the massif. An extraordinary rainfall, combined with the high recharge of the aquifers, was needed to release the slushflows. The hydrogeological behaviour of the massif was also the main factor controlling the location of the slushflow starting zones.

Three factors explain the very low frequency of the slushflows: the exceptional rainfall, the karstic structure of the massif and the snowpack properties. The rainfall was highly unusual, as the data in Table 2 demonstrate, and occurred when there was a winter snow cover. The great water supply produced by the rainfall was the main factor in the release of the slushflows. The epikarstic aquifers of the karstic system act as water-storage units, so the springs become active depending on the previous storage state of the aquifers and on their recharge. As a result, not all intense winter rainfalls activate the springs, so slushflow release is less frequent than intense rainfall.

On the other hand, due to the low latitude and the altitude of this area, ice crusts develop easily during winter and are commonly found in the snowpack, which then becomes very stable and unfavourable to the release of slushflows (Hestnes and Bakkehøi, 1997). This was not the case when the slushflows released at the beginning of winter. In two cases the snowpack was compacted on the pistes and was homogeneous. Away from the pistes the snow cover was also homogeneous and had a high porosity, conditions which favour slushflow release.

The slushflows at El Port del Comte were unusual events. Given their very low frequency they are only a minor risk for the ski resort. In the future they could probably be avoided by excavating some drainage channels at an oblique angle to the pistes to improve and control water runoff from the springs and the concavities of the slopes.

Slushflows are closely related to karstic springs. There are a number of such springs on the massif. A spatial prediction of areas threatened by potential slushflows could be made and, if recommended, some aquifers could be controlled and drained.

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