Runoff and Sediment Transport during the Snowmelt Period in a Mediterranean High-Mountain Catchment

Authors: Lana-Renault, Noemí, Alvera, Bernardo, and García-Ruiz, José M.

Source: Arctic, Antarctic, and Alpine Research, 43(2) : 213-222

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1938-4246-43.2.213

Arctic, Antarctic, and Alpine Research, Vol. 43, No. 2, 2011, pp. 213–222

Runoff and Sediment Transport during the Snowmelt Period in a Mediterranean High-Mountain Catchment

*Noemí Lana-Renault**§
Bernardo Alvera† *and*
José M. García-Ruiz‡

*Corresponding author: Área de Geografía, Departamento de Ciencias Humanas, Universidad de La Rioja, 26004, Logroño, Spain
noemi-solange.lana-renault@unirioja.es
†Instituto Pirenaico de Ecología, CSIC, Apdo. 64, 22700 Jaca, Spain
‡Instituto Pirenaico de Ecología, CSIC, Campus de Aula Dei, Apdo. 13034, 50080 Zaragoza, Spain
§Department of Physical Geography, Faculty of Geosciences, Utrecht University, P.O. Box 80115, 3508 TC Utrecht, The Netherlands

Abstract

The hydrological and geomorphic functioning of high-mountain catchments is heavily influenced by snow accumulation and melt processes, which condition the timing and characteristics of discharges, solute outputs, and suspended sediment and bedload transport. We report here the transport of suspended sediment and solutes during the snowmelt period in a small experimental catchment in the subalpine belt of the Central Spanish Pyrenees. The seasonality of hydrological and sediment responses throughout the year was investigated using daily data of discharge, suspended sediment transport and solute outputs of the hydrological years 2003/2004 and 2005/2006. The study demonstrated the importance of the snowmelt period in terms of runoff production, and solute and suspended sediment yield: whereas precipitation during the snowmelt period (2–2.5 months) represented 10–13% of annual precipitation, discharge and suspended sediment transport accounted for up to 50% and 60%, respectively, and solute output approximately 40–50%. Solute transport dominated throughout the snowmelt period, whereas suspended sediment transport mostly occurred during the second phase of the snowmelt period (June), when an expanding area of the catchment was free from snow. The moderate daily increases in discharge, which were related to day–night temperature fluctuations, were insufficient to transport bedload material. Hourly data were used for preliminary assessment of the relationships among discharge, suspended sediment, and solute concentration, which provided insights into sediment sources and delivery mechanisms. Thus, during snowmelt-related events, the sediment mobilized was most probably derived from areas near or within the channel. In contrast, during events involving both snowmelt and rainfall, the gully system near the divide contributed to sediment load. The solute concentration was inversely related to water discharge, with higher concentrations during the first half of the snowmelt period (May) than during the second half (June). The results of this study demonstrate the key role of snow accumulation and melting processes in controlling the hydrological dynamics and patterns of particulate and solute mobilization in high-mountain environments. Future changes in snow volume and duration will affect the timing of snowmelt-related spring high flows, as well as soil erosion and transport.

DOI: 10.1657/1938-4246-43.2.213

Introduction

High mountains typically store large quantities of water in the form of snow, which can contribute to major flood events during melt periods, augment early summer base flows, and significantly influence the chemical and ecological characteristics of streams (Williams and Melack, 1991; Soulsby et al., 1997). Snow accumulation and subsequent melting also play very important geomorphological roles linked to freeze–thaw processes, shallow landsliding, solifluction, rilling, and sheet-wash erosion, which result in significant sediment yields (Barsch and Caine, 1984).

Rivers in lowland areas are often fed by meltwater from high mountains, and in these situations an understanding of the hydrological dynamics and sediment delivery processes is essential. This is of particular importance in Mediterranean basins, which receive sparse and irregular precipitation and rely on water management based largely on reservoirs that depend on runoff generated in mountain areas (López-Moreno and García-Ruiz, 2004). Furthermore, interest has recently increased because of the predictions of pronounced effects of climate change in southern Europe (Beniston, 2003; López-Moreno et al., 2008a). Amongst the most significant potential effects are a decrease in the importance of snow accumulation in winter (López-Moreno, 2005) and a progressive shift of streamflow from spring snowmelt to winter runoff (Arnell, 1999a, 1999b; López-Moreno and García-Ruiz, 2004). This is of great relevance to the Mediterranean region, where snow accumulation and melt control discharge, and result in the spring and summer discharges being more reliable (Viviroli et al., 2003; García-Ruiz et al., 2011). The strategic importance of the hydrological functioning of mountain areas has spurred research aimed at understanding runoff generation and sediment yield in a changing environment. Many catchments have been monitored, but most are located at low–medium altitudes. A lower number of catchments has been studied

1523-0430/11 $7.00

in high-mountain areas, primarily because of limited accessibility and the difficulties in obtaining continuous and reliable data, particularly because of the involvement of snowfall and the persistence of snowpack covering the soil. High-mountain catchments studies focused on the characteristics and temporal variability of snow cover (e.g. Stähli and Gustafsson, 2006; Fassnacht et al., 2010) and biogeochemical aspects of high-altitude environments, especially in the Sierra Nevada (e.g. Williams and Melack, 1991; Leydecker et al., 2001; Williams et al., 2001) and Colorado (e.g. Denning et al., 1991; Brooks and Williams, 1999; Williams et al., 2009). Fewer studies, including some in the Swiss Alps (e.g. Rickenmann, 1997; Hegg et al., 2006), have investigated suspended and bedload sediment transport.

The Izas catchment, in the subalpine belt of the Central Spanish Pyrenees, was established in 1987 as a monitoring site for snowmelt processes and the relationships among precipitation, snow accumulation, water discharge, and sediment transport in a high-mountain environment. Since that time the catchment has provided information on snowmelt modeling (Anderton et al., 2002) and sediment transport processes, especially those related to the relationships between flood magnitude and grain size distribution of bedload (Martínez-Castroviejo et al., 1991; White et al., 1997), the inter-annual variability of bedload (Alvera and García-Ruiz, 2000), and the geomorphic consequences of extreme hydrological events (Díez et al., 1988). Measurements on suspended sediment transport and solute outputs have been difficult in this catchment, and studies have mostly been based on estimates derived from data collected over short-term periods (García-Ruiz et al., 2010). Unfortunately, for only two snowmelt periods (2003/2004 and 2005/2006) is there a complete record of precipitation, air temperature, snow accumulation and melt, discharge, and solute and suspended sediment concentrations, primarily because of problems associated with continuously recording sediment data and the fact that snow depth has only recently been monitored. Nevertheless, this information improves notably the contribution provided by previous papers, especially for runoff and sediment transport during the snowmelt period, which has been scarcely studied in Mediterranean mountains and, in particular, in the Izas catchment. In the present study, the sediment response of the Izas catchment was investigated during the snowmelt period and compared to the whole year, to assess the relative importance of this period in terms of runoff and sediment yield, and to study the effect of daily and seasonal hydrological variability on sediment mobilization and export.

Study Area

The Izas catchment (0.33 km^2) is located in the Upper Gállego River valley, Central Spanish Pyrenees, between 2060 and 2280 m a.s.l. (Fig. 1). Mean annual temperature is approximately 4 °C, and mean annual precipitation is approximately 2000 mm, with most precipitation occurring between October and May. From mid-October to April, precipitation falls as snow, which usually covers the catchment until June. The snowmelt season occurs in May and June, though short melting periods can occur even in winter, coinciding with relatively warm events.

The catchment faces east, and is composed of a glacially scoured cirque with steep gradients (slopes 25–30°) in the upper part, and gentle slopes (<5°) in the lower part over fluvial and colluvial sediments. The bedrock is densely fractured Carboniferous slate. The dominant geomorphic process is mass movements of varying size. Solifluction is very active in deep soils, especially in the middle and lower parts of north-facing slopes (Del Barrio and Puigdefábregas, 1987) (Fig. 1). Most soils of south-facing slopes are covered by gelifluction terracettes. A dense and steep gully system occurs close to the divide (Fig. 2), where gelifraction processes supply abundant clasts to the fluvial system. This small area, representing about 5% of the catchment, is the most important sediment source for the main channel (Díez et al., 1988). Subalpine and alpine grasslands (*Festuca eskia*, *Nardus stricta*) cover most of the slopes.

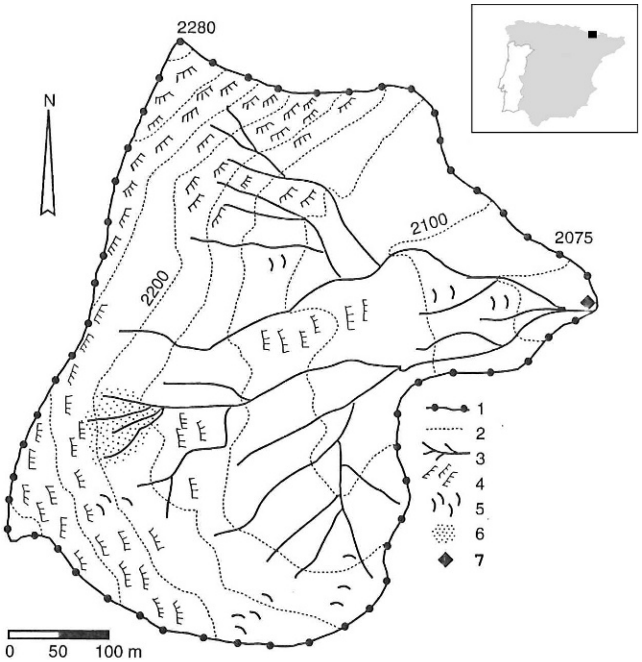

FIGURE 1. The main geomorphic features of the Izas catchment (located at 42°44′N, 0°25′W), including (1) the main divide, (2) contour levels, (3) the fluvial network, (4) terracettes, (5) solifluction lobes, (6) the main sediment source, and (7) the location of the measurement site.

Equipment and Methods

A gauging station (120° V-notch weir) is located at the outlet of the catchment, allowing continuous recording of water discharge and sediment transport. The water level and temperature are measured with a pressure transducer (capacitive OTT PLS) and a thermistor (Campbell 247), respectively. Suspended and dissolved-solid concentrations are obtained using a conductivity meter (Campbell 247), and a turbidity meter (McVan Analite NEP9500). The turbidity meter was previously calibrated in the laboratory using 15 water samples with material from the catchment. The conductivity meter was calibrated using 32 water samples taken from the stream during autumn and spring. The calibration of both devices was conducted five times following installation to test its robustness through time. All these variables are measured every minute, and averaged and recorded (Datataker 505 and Campbell CR10X data loggers) every five minutes. Conductivity (µS/cm) and turbidity (NTU) measurements are converted to concentration (mg L^{-1}) using regressions determined during calibration. Solutes and suspended sediment yield were obtained using concentrations (C, mg L^{-1}) and discharge data (Q, L s^{-1}) (C · Q · time). Bedload transport (mainly particles greater than 2 mm; Martínez-Castroviejo et al., 1991) is monitored using a 600–750 kg capacity slot trap located in the stream bed.

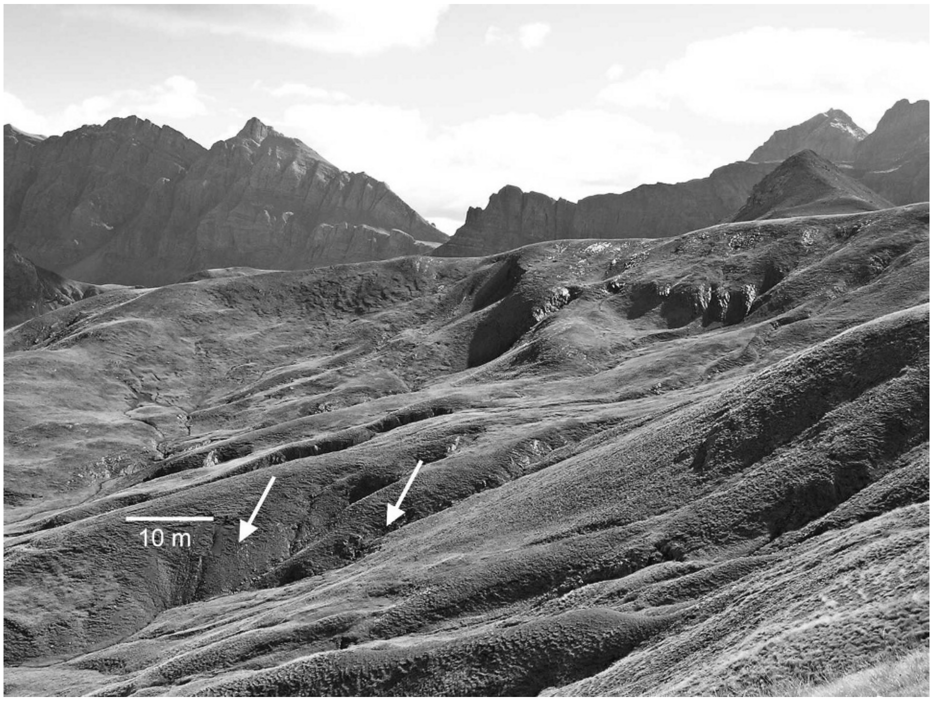

FIGURE 2. The dense gully network on Carboniferous slates close to the divide (pointed by the white arrows) is the main sediment source area in the catchment.

Periodically, usually after heavy storms and at the end of the snowmelt period, the trap is emptied and the volume of sediment weighed. An automatic weather station records information on air temperature and relative humidity (measured every minute and averaged every hour; Vaisala HMP45A/D probe), solar radiation (in/out; Kipp & Zonen CNR1 radiometer), wind velocity and direction (Young 03002 wind sentry set), and precipitation (Geonor T-200BM weighing vibrant wire gauge with Alter wind shield, 0.1 mm). Information on the snow pack is obtained from an ultrasonic ranging sensor (Campbell SR 50) and a snow pillow with a pressure probe (Sommer USH-8) located close to the flume, where snowmelt ends rapidly relative to the rest of the catchment. It is important to note that most of the catchment remained covered by snow whilst the snow pillow was free of snow, and for this reason the discharge characteristics were typical of the snowmelt period (May–June), even though the snow depth is zero in the graph. Temporal estimates of the area covered by snow were obtained during periodic visits to the catchment. For instance, it was found that the area covered by snow declined from May to July 2004 as follows: 99% (14 May), 90% (25 May), 80% (29 May), 60% (3 June), 50% (10 June), 30% (17 June), 10% (23 June), and 1% (8 July). A maximum snow accumulation of about 1.5 m was recorded at the beginning of April 2004, and at the beginning of March 2006.

Extreme conditions, especially during winter and spring, restrict access to monitoring devices under the snow (e.g. the conductivity and turbidity meters), thus reducing the availability of some data. As a consequence, few data series provide complete and reliable information for entire water years. In the present study, information on precipitation, air temperature, discharge, snow accumulation, and solute and suspended sediment transport for the two water years (October to September) 2003/2004 and 2005/2006 was used. The relative contributions of solute outputs, suspended sediment, and bedload yield were calculated for the snowmelt period and for the year as a whole. Hourly data were used to analyze the relationship of discharge to suspended and dissolved sediment transport.

Results and Discussion

Annual values of precipitation, runoff, runoff coefficient, suspended sediment, and bedload and solute outputs for the two water years analyzed in the study are listed in Table 1. The annual runoff coefficients for the Izas catchment for 2003/2004 and 2005/2006 (0.92 and 0.86, respectively) were particularly high in relation to typically high annual precipitation values and low evapotranspiration rates. However, they are consistent with runoff coefficients for comparable high-mountain areas (Keller and Weibel, 1991; Jones and Post, 2004).

Suspended sediment and bedload outputs show high inter- and intra-annual variability, as they depend on the occurrence of intense flood events in summer and autumn (Díez et al., 1988). Thus, suspended sediment recorded values of 36.1 and 67.4 Mg km^{-2} in 2003/2004 and 2005/2006, respectively. In both years, bedload was recorded as 9.3 and 66.2 Mg km^{-2}, respectively. These differences were due to several large floods that occurred during October and September in the water year 2005/2006. Furthermore, a peak flow of almost 900 L s^{-1} (2727 L s^{-1} km^{-2}) was recorded at the end of September 2006, and this caused the transport of 22 Mg (66.2 Mg km^{-2}) of bedload. As reported previously, bedload transport in mountain catchments is characterized by enormous

TABLE 1

Annual precipitation, runoff, runoff coefficient (RC), and sediment yield in the Izas catchment for the water years 2003/2004 and 2005/2006.

	2003/2004	2005/2006
Precipitation (mm)	2155	2221
Runoff (mm)	1983	1916
RC (−)	0.92	0.86
Solutes (Mg km^{-2})	161.5	159.2
Suspended sediment (Mg km^{-2})	36.1	67.4
Bedload (Mg km^{-2})	9.3	66.2
Total sediment (Mg km^{-2})	206.9	292.8

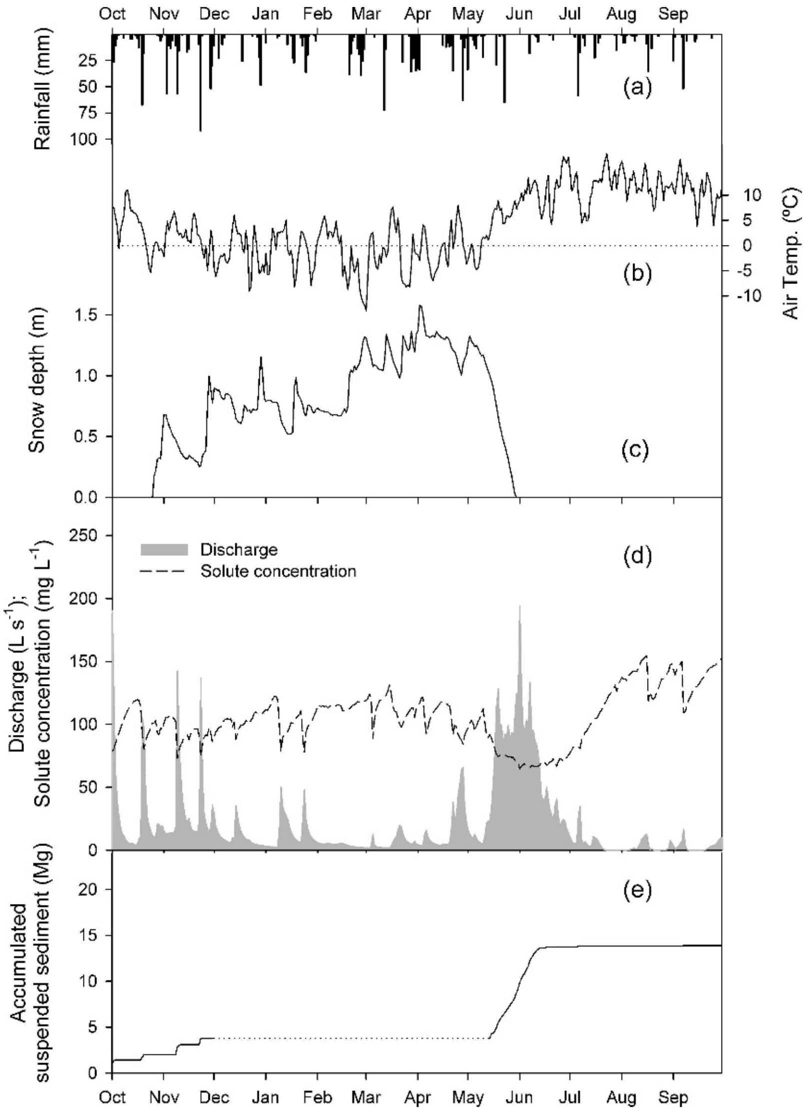

FIGURE 3. (a) Daily precipitation, (b) average daily temperature, (c) snowpack depth, (d) discharge and solute concentration, and (e) daily suspended sediment yield for the water year 2003/2004.

temporal variability, mainly related to the occurrence of heavy and less frequent storm floods (Hayward, 1980; Lenzi et al., 1999; Lana-Renault and Regüés, 2007). In many instances such events are also associated with the exhaustion of coarse material. In the Izas catchment this was clearly illustrated in October 1987, when one rainstorm event transported 17 Mg of bedload, but a second rainstorm event with a similar peak flow one week later carried only 0.48 Mg (Martínez-Castroviejo et al., 1991; Alvera and García-Ruiz, 2000).

Solute outputs were similar in 2003/2004 and 2005/2006 (161.5 Mg km^{-2} and 159.2 Mg km^{-2}, respectively), and much higher than those of suspended sediment transport and bedload. The results of previous studies suggest that solute outputs are relatively constant on an inter-annual basis, and that their dominance is related to the high chemical weathering rate of slate (Alvera and García-Ruiz, 2000).

The results for total solute and particulate output indicate erosion rates of 206.9 Mg km^{-2} in 2003/2004 and 292.8 Mg km^{-2} in 2005/2006, which are values consistent with the annual sediment yields estimated for the Izas catchment since 1987 (200–320 Mg km^{-2} yr^{-1}; Alvera and García-Ruiz, 2000). If only suspended sediment and bedload outputs are considered, then total sediment yield was 45.4 (2003/2004) and 133.6 (2005/2006) Mg km^{-2}. Although differences among high-mountain environments (gradient, bedrock, connectivity between slopes and channels) make comparisons difficult, it is notable that these values are slightly higher than those for other mountain areas (Hayward, 1980; Evans and Warburton, 2005), which is probably because of the high level of runoff produced in the Izas catchment, the massive presence of slates, the active sediment source in the headwater, and its connection to the fluvial network.

Figures 3 and 4 show the evolution of daily precipitation, average daily temperature, snowpack depth, discharge and solute concentration, and daily suspended sediment yield for the water years 2003/2004 and 2005/2006, respectively. In both cases the maximum daily rainfall usually occurred in autumn and spring. A period of increasing snow accumulation was evident from the end of October to April in 2003/2004 and from November to March in 2005/2006, coinciding with decreasing temperature. It is important to note that the falling section of the snow depth curve in Figures 3c and 4c is not representative of the entire catchment, as the measurements were made in the lower part of the catchment, close to the flume (see the Equipment and Methods section).

The evolution of water discharge throughout the year (Figs. 3d and 4d) showed a marked seasonal behavior typical of mountain rivers heavily influenced by snow (García-Ruiz et al., 2001). During autumn large fluctuations in discharge were recorded in response to intense rainfall events. The maximum

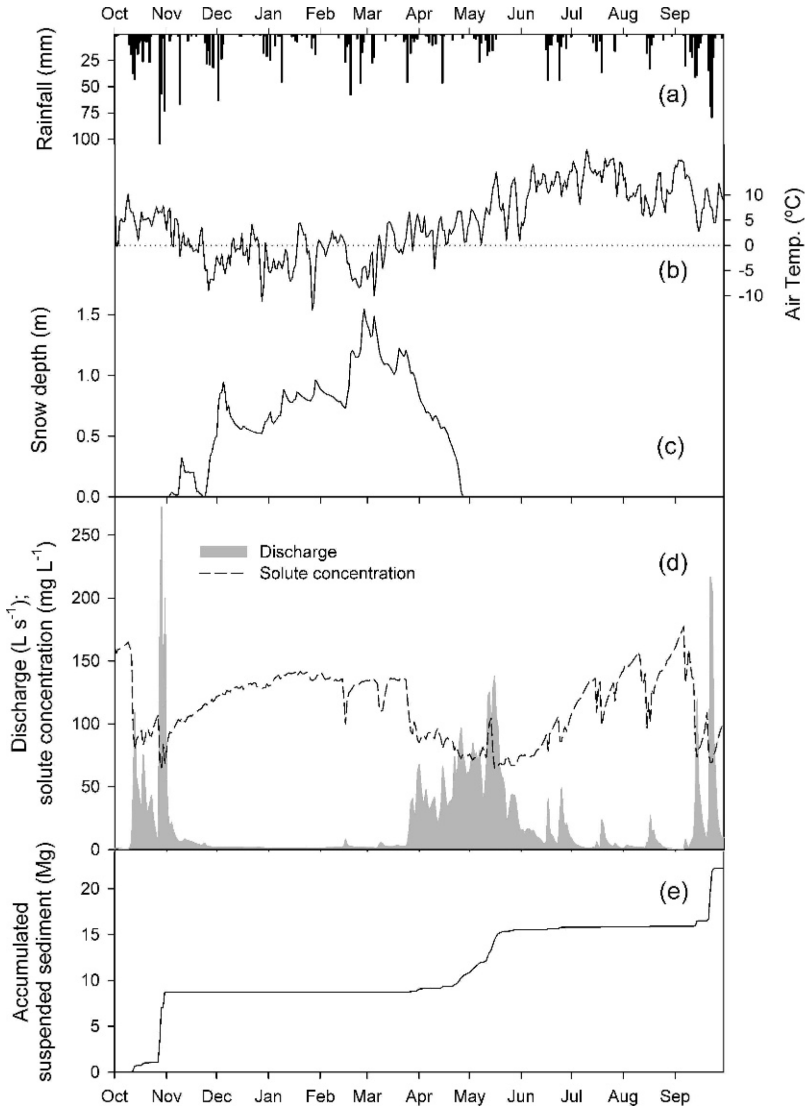

FIGURE 4. (a) Daily precipitation, (b) average daily temperature, (c) snowpack depth, (d) discharge and solute concentration, and (e) daily suspended sediment yield for the water year 2005/2006.

discharge in 2003/2004 occurred at the beginning of October with an instantaneous peak flow of almost 700 L s^{-1}. In 2005/2006 it occurred at the end of October, with an instantaneous peak flow of 880 L s^{-1}. Following the establishment of snow cover in the catchment, the increases in discharge occurred during short snowmelt periods, such as that at the end of November 2003, when part of the snow became streamflow because of the relatively high air temperature. During winter most of the precipitation was retained as snow because of the low temperatures, and discharge was very low and relatively constant, especially in February and March in 2003/2004, and between December and March in 2005/2006. The increase in temperature from the end of April in 2003/2004, and the end of March in 2005/2006, caused rapid melting of the snow cover in the catchment, particularly when the average daily temperature was above zero. This resulted in a very significant period of high flows starting in April and ending in June. Summer was characterized by low flows, with occasional intense storm events producing only small increases in discharge.

The solute concentration (Figs. 3d and 4d) fluctuated substantially throughout the year as a result of dilution processes associated with high volumes of discharge. This was clearly evident during the snowmelt period, when sustained high flows were associated with the lowest solute concentrations. The suspended sediment flux (Figs. 3e and 4e) was clearly correlated with the occurrence of high flood events in autumn and to the snowmelt period, indicating that these are the two most intense periods of hydrological and geomorphic activity in the catchment.

Table 2 shows the water, solute, and suspended sediment outputs during the snowmelt period for the two water years of the study, and their contributions to annual yield. Whereas precipitation contributed only 10–13%, runoff in both cases represented about 50% of the annual yield. Clearly, the large amounts of water produced in such short periods (2 months in 2003/2004 and

TABLE 2

Precipitation, runoff, and sediment yield during the snowmelt period (May–June) for the water years 2003/2004 and 2005/2006. Percentages in italics indicate the fraction of the annual output represented by the snowmelt period value.

	2003/2004	%	2005/2006	%
Precipitation (mm)	228.3	*11*	294.8	*13*
Runoff (mm)	954.7	*48*	1027.0	*54*
Solutes (Mg km^{-2})	68.2	*41*	81.6	*51*
Suspended sediment (Mg km^{-2})	22.0	*61*	20.5	*30*
Bedload (Mg km^{-2})	0	*0*	0	*0*
Total sediment (Mg km^{-2})	90.2	*43*	102.1	*35*

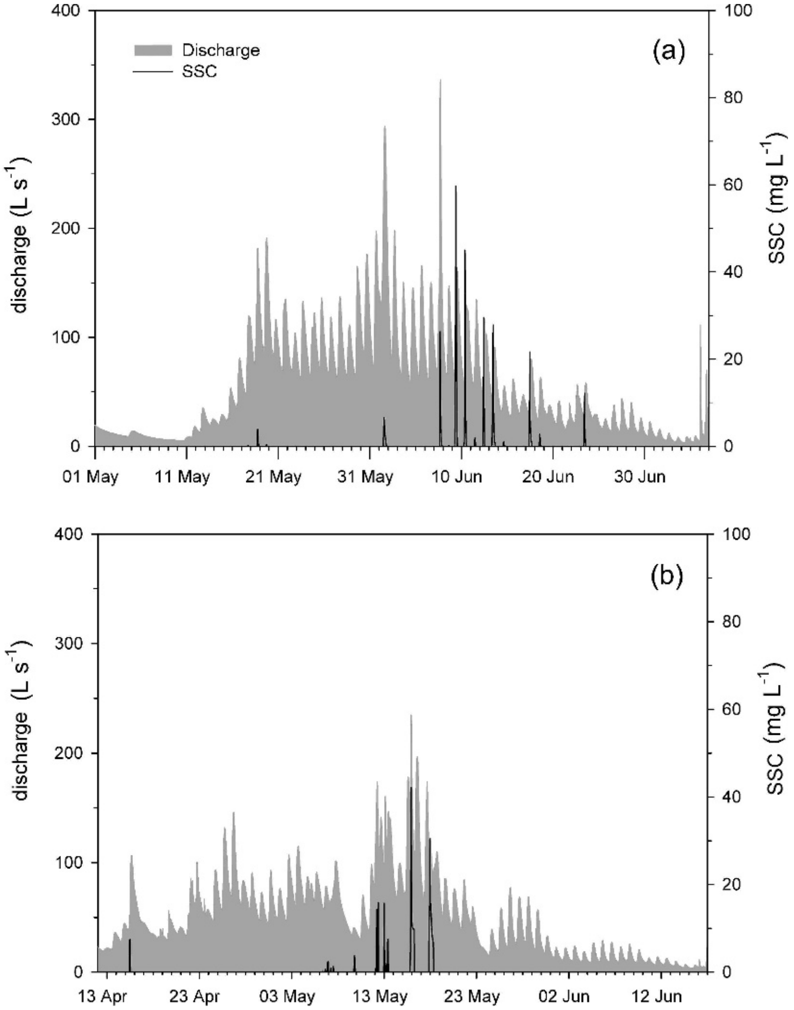

FIGURE 5. Hourly discharge and suspended sediment concentrations (SSC) during the 2004 (a) and 2006 (b) snowmelt period.

2.5 months in 2005/2006) were a consequence of previous snowfall, or rainfall accumulated in the form of snow.

The contribution of the snowmelt period to the annual solute and particulate yield was also very significant, representing 43% in 2003/2004 and 35% in 2005/2006. Solutes contributed approximately half the annual yield (41% and 51%, respectively) because their transport was highly related to discharge, as has been reported for other high-mountain catchments (Brooks and Williams, 1999; Williams et al., 2009). The relative contribution of suspended sediment during this period was more variable, as this depended on the amount of suspended sediment produced during flood events in the remainder of the year. The autumn and summer flood events in 2003/2004 were of smaller magnitude (lower discharge and sediment transport) than those in 2005/2006; thus, the relative contribution during the snowmelt period in 2003/2004 was much higher (61% vs. 30%). No bedload was recorded during the snowmelt period. This is similar to observations made in previous years by Alvera and García-Ruiz (2000), who suggested that bedload transport during the snowmelt was negligible because the peak flows were characterized by a gentle increase that was insufficient to mobilize coarse material. If the snowmelt period is considered in isolation, solute outputs largely dominated relative to suspended sediment outputs (about 75% and 25%, respectively).

Figure 5 shows the hourly discharge and SSC during the 2004 (a) and 2006 (b) snowmelt period. Typical daily pulses were evident, related to temperature oscillations between day and night. In 2004, the snowmelt period was characterized by a marked increase in discharge after 11 May, and a sustained period of continuous high flows between mid May and mid June. Base flow during this one month period increased over 15-fold, from 5 L s^{-1} to 80 L s^{-1}. Daily discharge pulses were less evident throughout the second half of June, when the spatial extent of snow was increasingly limited. Some peak flows related to greater increases in temperature were recorded, and on some occasions were accompanied by rainfall events. The maximum discharge was registered on 7 June, when a temperature increase to 10 °C with 19 mm of rainfall produced a peak flow of 336 L s^{-1}. Most of the suspended sediment was carried in the second part of the snowmelt period, when an increasing area of the catchment was free from snow. The maximum SSC (60 mg L^{-1}) was registered on 9 June, two days after the peak flow. In fact, the data indicate no direct relationship between peak flows and peaks in suspended sediment, suggesting that other factors, probably related to the location of the areas free from snow, were influencing suspended sediment mobilization and transport. In 2006, the increase in discharge at the beginning of the snowmelt period was influenced by large rainfalls that occurred through the end of March and the beginning of April. In this case, the maximum discharge (235 L s^{-1}) and maximum SSC (42 mg L^{-1}) were registered on 16 May, related to an increase of temperature up to 14 °C and 16 mm of rainfall.

Hourly SSC discharge hysteresis relationships (Fig. 6) were investigated because they often provide insights into sediment sources and the delivery mechanisms operating in a catchment. A clockwise hysteresis loop was observed for all analyzed events,

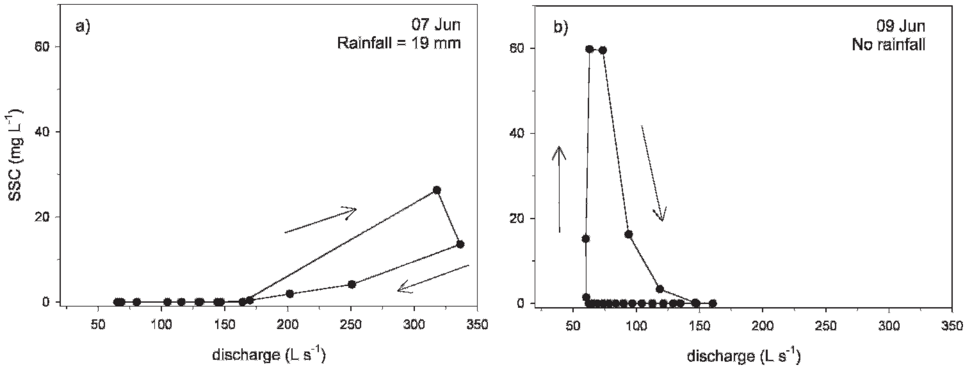

FIGURE 6. Relationships between hourly suspended sediment concentration (SSC) and discharge during an event involving rain on snow (a), and during a snowmelt-only event (b).

with higher SSCs in the rising limb of the stream flow hydrograph than at the same discharge in the falling limb. This is usually associated with rapid displacement and subsequent exhaustion of sediment from nearby sources, or with the remobilization of sediment previously deposited in the channel (Williams, 1989; Regüés et al., 2000; Seeger et al., 2004; Langlois et al., 2005; Lana-Renault and Regüés, 2009). Two patterns were observed, depending on whether the flood was related to an event involving rainfall on snow or to an event involving snowmelt only. Figure 6a shows the SSC-Q hysteresis loop during the event on 7 June 2004, which occurred in response to both snowmelt and rainfall. By then, about 50% of the catchment was free from snow, and rainfall fell directly on some of the bare soil areas. The suspended sediment peak occurred immediately before the peak flow, about 8 h after the beginning of the discharge increase. Figure 6b shows an example of a SSC-Q hysteresis loop during an event produced only by snowmelt following a temperature increase during the day (9 June 2004). In this case the sediment peak occurred at the very beginning of the rising limb, and the concentration abruptly decreased 1 h later, indicating rapid exhaustion of the sediment. A similar pattern was observed during the following days, associated with the daily discharge waves. Under these conditions the sediment was probably derived from areas close to the measurement point, such as material previously deposited in the channel, or sediment mobilized from the ravine banks as a consequence of snowmelt (Woo et al., 1992; Forbes and Lamoureux, 2005; Beylich et al., 2006; Dugan et al., 2009; McDonald and Lamoureux, 2009). In contrast, with rainfall events, the gully system near the divide and other bare areas were probably contributing to the sediment response, and consequently the sediment peak occurred later and almost in synchrony with the peak flow.

Average solute concentrations during the melting period were approximately 80 mg L^{-1} for the two water years studied, with peaks of 116 mg L^{-1} and 140 mg L^{-1} in 2004 and 2006, respectively. An inverse relationship was found between hourly discharge and solute concentrations. Figure 7 shows that for the 2004 snowmelt period there was an exponential decrease in solute concentration with increasing discharge. Díez et al. (1991) reported that this is the general pattern for solutes such as sodium, magnesium, and silica, which are derived from bedrock or the deeper soil horizons. It is notable that for the same water discharge, solute concentrations were always higher during the first half of the snowmelt period than during the second half. This pattern, which was also observed in the 2006 melting period, has been reported in other cold environments (Johannessen and Henriksen, 1978; Denning et al., 1991; Williams and Melack, 1991; Beylich et al., 2005). During the first half of the snowmelt period almost the entire Izas catchment was contributing to runoff (at the end of May, 80% of the catchment was still covered by snow), probably dominated by subsurface flow, as revealed by Alvera and Puigdefábregas (1985), who observed intense runoff flowing into small mammals burrows under the snowpack. Under these conditions runoff water is derived from the entire catchment, and because it flows long distances has the opportunity to dissolve more soil material. An increase in solute concentration with increased distance between the water source and stream channel has also been reported for other high-mountain catchments (Alvera and Puigdefábregas, 1985; Caine and Thurman, 1990). At the end of the melting period, snow becomes progressively limited to ravines, which have less vegetation and thinner soils because of erosion, and runoff from these areas would be expected to have lower levels of solutes.

The delicate relationships between snow accumulation and melt processes, and among discharge, solute outputs, and sediment transport, make high-mountain environments hydrologically sensitive to global changes in temperature and precipitation. These relationships affect water quality and availability, fluvial and riparian ecosystems, and water management (López-Moreno et al., 2008b). All climate models project a consistent trend towards warmer conditions (Gibelin and Dequé, 2003; Hertig and Jacobeit, 2008) and less precipitation (Goubanova and Li, 2007; Evans, 2009) in coming decades. According to model simulations (López-Moreno et al., 2008c, 2009; Stewart, 2009) the observed trends in snowpack and streamflow timing (earlier, and with less spring melting) in northern Spain (López-Moreno and García-Ruiz, 2004; López-Moreno, 2005; Santos-González et al., 2010) will continue and accelerate in the future. Based on the GRENBLS model under the IPCC emission scenario SRES A2, López-Moreno et al. (2008c) reported that the most important consequence in the Pyrenees will be a reduction of approximately

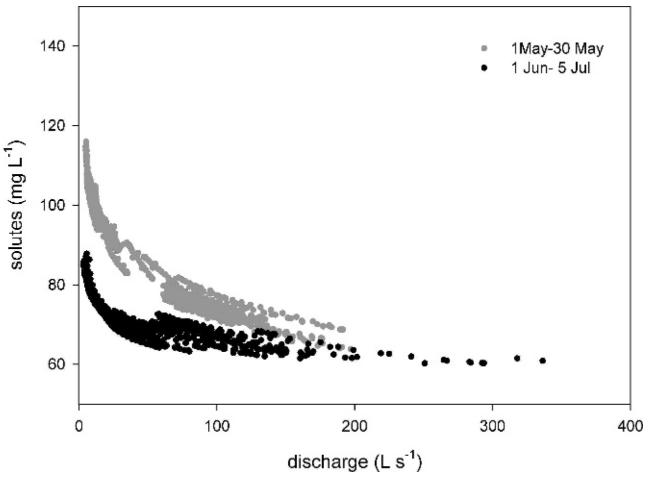

FIGURE 7. Relationships between hourly solute concentration and discharge during the 2004 snowmelt period.

two months in the duration of the snowpack. They also predicted large reductions in snow volume with increased temperature, but the effect was subject to strong vertical gradients and the emission scenario chosen. These factors indicate that major hydrological and geomorphic changes will occur in the Izas catchment, with snowmelt occurring earlier. This will result in an increase in erosion and suspended sediment transport because the loss of snow cover will expose the soil to rainfall in May and June. Based on studies in the Rocky Mountains, Williams et al. (1996) and Baron et al. (2000) concluded that even small changes in climate parameters can result in large changes in the hydrochemistry of alpine streams.

Conclusions

The hydrological and sedimentological responses of a high-mountain (the Izas) catchment influenced by snow were studied in the Central Spanish Pyrenees during the water years 2003/2004 and 2005/2006.

- (i) High annual runoff production was observed in the catchment, which is characteristic of environments where evapotranspiration is low.
- (ii) The estimated annual erosion rates (206.9 and 292.8 Mg km^{-2} for 2003/2004 and 2005/2006, respectively) were within the typical long-term values for similar catchments. The annual sum of material exported was largely dominated by solutes, whereas suspended sediment and bedload transport depended on the occurrence of intense flood events.
- (iii) The two-month snowmelt period contributed about 50% of the total annual runoff and 35–43% of the total solute and suspended sediment yield. This demonstrates the hydrological and geomorphic importance of this brief period in the year.
- (iv) During the snowmelt period most material was exported in the form of solutes (>75%) and the remainder was suspended sediment. Bedload did not occur during the snowmelt period because daily pulses in discharge were of insufficient energy to move coarse sediments (>2 mm).
- (v) Different discharge–sediment relationships were observed for solutes and suspended sediment transport, indicating great complexity in catchment function during the snowmelt period. The daily SSC–discharge hysteresis relationships were always clockwise, indicating rapid displacement of sediment near or within the channel. However, the analysis revealed two patterns, suggesting the involvement of different sediment sources and sediment delivery mechanisms during events involving rainfall on snow, and those involving snowmelt.
- (vi) The solute concentration was inversely related to water discharge. It varied throughout the snowmelt period, with higher concentrations occurring during the first half of the snowmelt period and lower concentrations during the second half.

This study has highlighted the hydrological and geomorphic importance of the snowmelt period in catchments influenced by snow, and demonstrates that complex interactions are involved in solute and sediment delivery during this period. Ongoing studies in the Izas catchment using longer data series, field observations, and more detailed analysis of sediment transport (e.g. the chemical properties of the solutes) will enable identification of the dominant hydrological processes and assessment of sediment accessibility from hillslopes. This is of great importance from a hydrogeomorphic point of view as it will increase understanding of the functioning of snow-influenced mountain environments, which to date have received relatively little attention in the Mediterranean region. Changes in snow volume and the duration of the snowpack will affect the timing of snowmelt-related spring high flows, and both solute outputs and SSCs.

Acknowledgments

Support for this research was provided by the following projects: "Processes and sediment balances at different spatial scales in Mediterranean environments: effects of climate fluctuations and land use changes–PROBASE" (CGL2006-11619/HID CONSOLIDER), funded by the Spanish Ministry of Education and Science, and "Assessing climatic change and impacts on the quantity and quality of water–ACQWA" (FP7-ENV-2007-1-212250), financed by the European Commission. Monitoring of the catchment was supported by an agreement between the CSIC and the Spanish Ministry of Environment (RESEL). The first author benefited from a research contract (I+D+I 2008-2011 National Program) funded by the Spanish Ministry of Education and Science.

References Cited

Alvera, B., and García-Ruiz, J. M., 2000: Variability of sediment yield from a high mountain catchment, Central Spanish Pyrenees. *Arctic, Antarctic, and Alpine Research*, 32: 478–484.

Alvera, B., and Puigdefábregas, J., 1985: Pulsación diaria de la carga suspendida y disuelta en la escorrentía de fusion nival. *Cuadernos de Investigación Geográfica*, 11: 5–20.

Anderton, S. P., White, S. M., and Alvera, B., 2002: Micro-scale spatial variability and the timing of snow melt runoff in a high mountain catchment. *Journal of Hydrology*, 268: 158–176.

Arnell, N. W., 1999a: Climate change and global water resources. *Global Environmental Change*, 9: S31–S49.

Arnell, N. W., 1999b: The effect of climate change on hydrological regimes in Europe: a continental perspective. *Global Environmental Change*, 9: 5–23.

Baron, J. S., Hartman, M. D., Band, L. E., and Lammers, R. B., 2000: Sensitivity of a high-elevation Rocky Mountain watershed to altered climate and $C0_2$. *Water Resources Research*, 36(1): 89–99.

Barsch, D., and Caine, N., 1984: The nature of mountain geomorphology. *Mountain Research and Development*, 4: 287–298.

Beniston, M., 2003: Climatic change in mountain regions: a review of possible impacts. *Climatic Change*, 59: 5–31.

Beylich, A. A., Molau, U., Luthbom, K., and Gintz, D., 2005: Rates of chemical and mechanical fluvial denudation in an arctic oceanic periglacial environment, Latnjavagge drainage basin, northernmost Swedish Lapland. *Arctic, Antarctic, and Alpine Research*, 37: 75–87.

Beylich, A. A., Sandberg, O., Molau, U., and Wache, S., 2006: Intensity and spatio-temporal variability of fluvial sediment transfers in an Arctic-oceanic periglacial environment in northernmost Swedish Lapland (Latnjavagge catchment). *Geomorphology*, 80: 114–130.

Brooks, P. D., and Williams, M. W., 1999: Snowpack controls on N cycling and export in seasonally snow-covered catchments. *Hydrological Processes*, 13: 2177–2190.

Caine, N., and Thurman, E. M., 1990: Temporal and spatial variations in the solute content of an alpine stream, Colorado Front Range. *Geomorphology*, 4: 55–72.

Del Barrio, G., and Puigdefábregas, J., 1987: Mass wasting features above the timberline in the Central Pyrenees and their topographic controls. *Pirineos*, 130: 3–25.

Denning, A. S., Baron, J., Mast, M. A., and Arthur, M., 1991: Hydrologic pathways and chemical composition of runoff during snowmelt in Loch Vale watershed, Rocky Mountain National Park, Colorado, USA. *Water, Air, and Soil Pollution*, 59: 107–123.

Díez, J. C., Alvera, B., Puigdefábregas, J., and Gallart, F., 1988: Assessing sediment sources in a small drainage basin above timberline in the Pyrenees. *IAHS Publication*, 174: 197–205.

Díez, J. C., Alvera, B., Del Barrio, G., and Puigdefábregas, J., 1991: Streamflow water chemistry relationships in the alpine environment: a case study in a Pyrenean watershed. *Mitteilungsblatt des Hydrographischen Dienstes in Österreich*, 65–66: 119–123.

Dugan, H. A., Lamoureux, S. F., Lafreniere, M. J., and Lewis, T., 2009: Hydrological and sediment yield response to summer rainfall in a small high Arctic watershed. *Hydrological Processes*, 23: 1514–1526.

Evans, J., and Warburton, J., 2005: Sediment budget for an eroding peat-moorland catchment in northern England. *Earth Surface Processes and Landforms*, 30: 557–577.

Evans, J. P., 2009: 21st century climate change in the Middle East. *Climatic Change*, 92: 417–432.

Fassnacht, S. R., Heun, C. M., López-Moreno, J. I., and Latron, J., 2010: Variability of snow density measurements in the Rio Esera Valley, Pyrenees Mountains, Spain. *Cuadernos de Investigación Geográfica*, 36(1): 59–72.

Forbes, A. C., and Lamoureux, S. F., 2005: Climatic controls on streamflow and suspended sediment transport in three large Middle Arctic catchments, Boothia Peninsula, Nunavut, Canada. *Arctic, Antarctic, and Alpine Research*, 37: 304–315.

García-Ruiz, J. M., Beguería, S., López-Moreno, J. I., Lorente, A., and Seeger, M., 2001: *Los recursos hídricos superficiales del Alto Aragón y su evolución reciente*. Logroño: Geoforma Ediciones, 192 pp.

García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S., Lasanta, T., and Beguería, S., 2011: Mediterranean water resources in a global change scenario. *Earth Science Reviews*, doi: 10.1016/j.earscirev.2011.01.006.

García-Ruiz, J. M., Lana-Renault, N., Beguería, S., Lasanta, T., Regüés, D., Nadal-Romero, E., Serrano-Muela, P., López-Moreno, J. I., Alvera, B., Martí-Bono, C., and Alatorre, L. C., 2010: From plot to regional scales: interactions of slope and catchment hydrological and geomorphic processes in the Spanish Pyrenees. *Geomorphology*, 120: 248–257.

Gibelin, A. L., and Dequé, M., 2003: Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. *Climate Dynamics*, 20: 327–339.

Goubanova, K., and Li, L., 2007: Extremes in temperature and precipitation around the Mediterranean basin in an ensemble of future climate scenario simulations. *Global and Planetary Change*, 57: 27–42.

Hayward, J. A., 1980: *Hydrology and Stream Sediment from Torlesse Stream Catchment*. Canterbury: Tussock Grasslands and Mountain Lands Institute, 235 pp.

Hegg, C., McArdell, B. W., and Badoux, A., 2006: One hundred years of mountain hydrology in Switzerland by the WSL. *Hydrological Processes*, 20: 371–376.

Hertig, E., and Jacobeit, J., 2008: Downscaling future climate change: temperature scenarios for the Mediterranean area. *Global and Planetary Change*, 63: 127–131.

Johannessen, M., and Henriksen, A., 1978: Chemistry of snow melt water: changes in concentration during melting. *Water Resources Research*, 14: 615–619.

Jones, J. A., and Post, D. A., 2004: Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. *Water Resources Research*, 40: article W05203, doi:10.1029/2003WR002952.

Keller, H. M., and Weibel, P., 1991: Suspended sediments in streamwater—Indicators of erosion and bed load transport in mountainous basins. *IAHS Publication*, 203: 53–61.

Lana-Renault, N., and Regüés, D., 2007: Bedload transport under different flow conditions in a human-disturbed catchment in the Central Spanish Pyrenees. *Catena*, 71: 155–163.

Lana-Renault, N., and Regüés, D., 2009: Seasonal patterns of suspended sediment transport in an abandoned farmland catchment in the Central Spanish Pyrenees. *Earth Surface Processes and Landforms*, 34: 1291–1301.

Langlois, J. L., Johnson, D. W., and Mehuys, G. R., 2005: Suspended sediment dynamics associated with snowmelt runoff in a small mountain stream of Lake Tahoe (Nevada). *Hydrological Processes*, 19: 3569–3580.

Lenzi, M. A., D'agostino, V., and Billi, P., 1999: Bedload transport in the instrumented catchment of the Rio Cordon. Part I: Analysis of bedload records, conditions and threshold of bedload entrainment. *Catena*, 36: 171–190.

Leydecker, A., Sickman, J. O., and Melack, J. M., 2001: Spatial scaling of hydrological and biogeochemical aspects of high-altitude catchments in the Sierra Nevada, California, U.S.A. *Arctic, Antarctic, and Alpine Research*, 33(4): 391–396.

López-Moreno, J. I., 2005: Recent variations of snowpack depth in the Central Spanish Pyrenees. *Arctic, Antarctic, and Alpine Research*, 37(2): 253–260.

López-Moreno, J. I., and García-Ruiz, J. M., 2004: Influence of snow accumulation and snowmelt on streamflow in the Central Spanish Pyrenees. *Hydrological Sciences Journal*, 49: 787–802.

López-Moreno, J. I., Goyette, S., and Beniston, M., 2008a: Climate change prediction over complex areas: spatial variability of uncertainties and expected changes over the Pyrenees from a set of regional climate models. *International Journal of Climatology*, 28: 1535–1550.

López-Moreno, J. I., García-Ruiz, J. M., and Beniston, M., 2008b: Environmental change and water management in the Pyrenees. Facts and future perspectives for Mediterranean mountains. *Global and Planetary Change*, 66(3–4): 300–312.

López-Moreno, J. I., Goyette, S., Beniston, M., and Alvera, B., 2008c: Sensitivity of the snow energy balance to climatic changes: implications for the evolution of snowpack in the Pyrenees in the 21st century. *Climate Research*, 36: 203–217.

López-Moreno, J. I., Goyette, S., and Beniston, M., 2009: Impact of climate change on snowpack in the Pyrenees: Horizontal spatial variability and vertical gradients. *Journal of Hydrology*, 374: 384–396.

Martínez-Castroviejo, R., García-Ruiz, J. M., Díez, J. C., and Alvera, B., 1991: Coarse sediment transport in an experimental high mountain catchment of Central Pyrenees, Spain. *Zeitschrift für Geomorphologie Supplement Band*, 83: 105–114.

McDonald, D. M., and Lamoureux, S. F., 2009: Hydroclimatic and channel snowpack controls over suspended sediment and grain size transport in a High Arctic catchment. *Earth Surface Processes and Landforms*, 34: 424–436.

Regüés, D., Balasch, J. C., Castelltort, X., Soler, M., and Gallart, F., 2000: Relación entre las tendencias temporales de producción de sedimentos y las condiciones climáticas en una pequeña cuenca de montaña mediterránea (Vallcebre, Pirineos orientales). *Cuadernos de Investigación Geográfica*, 26: 41–65.

Rickenmann, D., 1997: Sediment transport in Swiss torrents. *Earth Surface Processes and Landforms*, 22: 937–951.

Santos-González, J., Redondo-Vega, J. M., Gómez-Villar, A., and González-Gutiérrez, R. B., 2010: Dinámica actual de los nichos de nivación del Alto Sil (Cordillera Cantábrica). *Cuadernos de Investigación Geográfica*, 36(1): 87–106.

Seeger, M., Errea, M. P., Beguería, S., Arnáez, J., Martí, C., and García-Ruiz, J. M., 2004: Catchment soil moisture and rainfall characteristics as determinant factors for discharge/suspended sediment hysteretic loops in a small headwater catchment in the Spanish Pyrenees. *Journal of Hydrology*, 288: 299–311.

Soulsby, C., Helliwell, R. C., Ferrier, R. C., Jenkins, A., and Harriman, R., 1997: Seasonal snowpack influence on the hydrology of a sub-arctic catchment in Scotland. *Journal of Hydrology*, 192: 17–32.

Stähli, M., and Gustafsson, D., 2006: Long-term investigations of the snow cover in a subalpine semi-forested catchment. *Hydrological Processes*, 20(2): 411–428.

Stewart, I. T., 2009: Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes*, 23: 78–94.

Viviroli, D., Weingartner, R., and Messerli, B., 2003: Assessing the hydrological significance of the world's mountains. *Mountain Research and Development*, 23: 32–40.

White, S., García-Ruiz, J. M., Martí, C., Alvera, B., and Del Barrio, G., 1997: Sediment transport in a high mountain catchment in the Central Spanish Pyrenees. *Physics and Chemistry of the Earth*, 22: 377–380.

Williams, G. P., 1989: Sediment concentration versus water discharge during single hydrological events in rivers. *Journal of Hydrology*, 111: 89–106.

Williams, M. R., Leydecker, A., Brown, A. D., and Melack, J. M., 2001: Processes regulating the solute concentrations of snowmelt runoff in two subalpine catchment of the Sierra Nevada, California. *Water Resources Research*, 37(7): 1993–2008.

Williams, M. W., and Melack, J. M., 1991: Solute chemistry of snowmelt runoff in an alpine basin, Sierra Nevada. *Water Resources Research*, 27: 1575–1588.

Williams, M. W., Losleben, M., Caine, N., and Greenland, D., 1996: Changes in climate and hydrochemical responses in a high elevation catchment in the Rocky Mountains, USA. *Limnology and Oceanography*, 41(5): 939–946.

Williams, M. W., Seibold, C., and Cowanski, K., 2009: Storage and release of solutes from a subalpine seasonal snowpack: soil and stream water response, Niwot Ridge, Colorado. *Biogeochemistry*, 95: 77–94.

Woo, M. K., Lewkowicz, A., and Rouse, W. R., 1992: Response of the Canadian permafrost environment to climatic change. *Physical Geography*, 13: 287–317.

MS accepted December 2010