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Bedload dynamics and associated snowmelt influence in mountainous and semiarid alluvial rivers

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ABSTRACT

The influence of snowmelt in semiarid alluvial rivers is determined by the river bed configuration and erosion processes. Moreover, the large amount of available sediment in the floodplains of these rivers limits traditional bedload sampling methodologies and suggests the use of large control volumes and long-term studies to understand erosive dynamics. In this study, bedload monitoring in a large control volume (0.2 hm^3) from 2004 to 2010 was used to study erosive processes of the Guadalfeo River, a semiarid alluvial river in southeastern Spain with high mountain influences and a hydrological regime conditioned by snow dynamics. The methodological approach to testing the performance of different transport models included characterization of the forcing agents (precipitation and snowmelt events), hydraulic configuration of the river, determination of the river bed material (surface and substrate), and one-off measurements for particular events. The results indicate a sediment volume–effective runoff relationship that is consistent with the existence of steep channels with a flashy runoff regime, although the existence of an armored layer derived from snowmelt events greatly controls the transport dynamics, with equivalent fractions of cobble–gravel and sand in the measured bedload. This apparent predominance of near-equal mobility was confirmed by the calibrated hiding function exponent ($x \approx 0.94$–0.97). The thresholds for entrainment and transport efficiency are similar to those observed for mountain rivers that exhibit torrential flow, although notable differences can be observed in the dynamics of the processes. The strong performance of the original Meyer-Peter and Müller model (with $c = 8$) is shown to estimate the total transported volume associated with intense events when the variability of d_{50} is included in the analysis. However, this model does not sufficiently capture transport because of moderate events (rain or snowmelt) and thus underestimates bedload on medium and long timescales. The calibrated model of Parker–Klingeman adequately represents erosive dynamics, with τ_{r50}^{*} values between 0.03 and 0.041 for moderate and intense events, respectively, and a flow threshold of 14.2 $m^3\,s^{-1}$ that separates these two situations. Nevertheless, these models based on *hiding functions* present greater dispersion if the variability of diameters related to cobbles and pebbles is considered. For such cases, the Wilcock and Crowe model performed better for both intense and moderate events. The latter is important in the study area, where snowmelt pulses occasionally exceed the critical flow and break the surface layer with significant sediment contributions. These processes differentiate the transport dynamics from other studies and are distinctive characteristics that are more closely related to mountainous influences in semiarid environments where pulses of intense snowmelt are common. Despite its limitations, the proposed methodology, based on a large check-dam, has proven to be adequate and representative for assessment of erosion processes.

1. Introduction

Fluvial processes in semiarid environments are of particular concern because of the uncertainty related to the frequency and magnitude of runoff events and because of the associated erosion–transport rates. In mountainous areas, topographic gradients and the resulting high variability of precipitation and temperature distributions may lead to occasionally large contributions of sediment as bedload, especially when wide floodplains retain large amounts of the available sediment. The existence of relevant snow coverage adds complexity to such processes, as snowmelt becomes an additional forcing agent for runoff events.

In such rivers, which are present in many regions of the world (such as the Atlas Mountains or Andean Cordillera), river bed configuration and flow regime are strongly influential on the modeling and prediction of bedload transport. For ephemeral streams without a *surface*, *pavement*, or *armor* layer (e.g., Schick, 1988; Martín-Vide et al., 1999;

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Table 1

Main statistical descriptors for weather stations in valley and mountain locations and for water flow at the Órgiva gauge station (Fig. 1), representative of the flow in the study area, as the contributions between the check-dam and gauge station can be considered negligible.[a]

		$\overline{X}_y$	σ_y	$X_{\max,d}$	$X_{\min,d}$
Mountain areas	P	629.73	127.60	51.78	0.01
(2000–2010)	T	6.48	0.35	25.28	−19.64
Valley areas	P	460.31	118.58	79.00	0.01
(2000–2010)	T	15.14	0.33	40.28	−15.00
Flow at Orgiva station ($m^3 s^{-1}$) (1990–2010)		3.79	5.91	112.40	0.13

[a] P precipitation (mm); T temperature (°C); $\overline{X}_y$ average annual data; σ_y typical annual deviation and $X_{\max,d}$ and $X_{\min,d}$ maximum and minimum daily values.

Table 3

Values of parameters C and A for estimating Q_c, Eq. (1), according to different authors [a].

C	A	
0.07	$(d_m/S_f)^{3/2}$	Meyer-Peter et al. (1934)
0.26 $[s\text{-}1]^{5/3}$	$(d_{40}/S_f^{0.78})^{3/2}$	Schoklitsch (1962)
0.15 $g_{1/2}$	$(d_{30}/S_f^{0.75})^{3/2}$	Bathurst et al. (1987)

[a] d_m, mean diameter of the bed material (m); g, acceleration of gravity ($m\ s^{-2}$); d_i, diameter of particle class i (m); $s = \rho_s/\rho$, specific gravity of the sediment with ρ and ρ_s the water density and sediment, respectively ($kg\ m^{-3}$); S_f is the friction slope ($m\ m^{-1}$).

Powell et al., 2001), variations in the Meyer-Peter and Müller model allow reasonable predictions based upon the relationship between bedload and shear stress (Reid et al., 1996, 1998; Reid, 2002). However, in near-perennial rivers associated with mountainous areas, the flow regime originating from snowmelt may allow partial rearrangement of the river bed and formation of a surface layer, hence adding greater complexity to bedload modeling. This configuration has been described by others (e.g., Batalla and Sala, 1995; Garcia et al., 2000; Lenzi, 2004; Lenzi et al., 2006; Batalla et al., 2010), mostly in torrential rivers — herein called steep channels with a flashy runoff regime — distant from arid floodplains. The existence of this layer, which largely determines the volume and dynamics of the bedload (Reid and Laronne, 1995), requires the integration of processes such as equal mobility and size-selective entrainment, discussed for decades by many other researchers (e.g., Egiazaroff, 1965; Parker and Klingeman, 1982; Ashworth and Ferguson, 1989; Parker and Toro-Escobar, 2002) because of their important effects on sediment transport.

Understanding this complexity is necessary for predicting the morphodynamic behavior of these rivers and proposing corrective and preventive guidelines. For this purpose, field observations are essential to validate the real applicability of transport models and to better define their potential and limitations (Surian, 2012). In dryland rivers, indirect approaches such as reservoir sedimentation studies have considerable advantages, given the ephemeral nature of the contributing events and associated volumes. Those methodologies provide information that integrates hydrologic, hydraulic, and sedimentological responses over a wide range of spatiotemporal scales (Powell, 2009).

This study examines the Guadalfeo River (southeastern Spain), a broad alluvial river in a coastal watershed linked to the Sierra Nevada mountains with semiarid conditions, where snow dynamics and heavy precipitation events result in significant bedload contributions. These contributions, which over the last 6000 years have led to the formation of a 50-km^2 coastal plain (Hoffmann, 1987), have also caused considerable economic and human losses (Capel, 1974; Ávila, 2007). When the Rules dam (110 hm^3) was built in 2004, an in-stream check-dam was constructed 9 km upstream (Fig. 1) to decrease the equilibrium channel slope, which represents the maximum efficiency in transporting sediment, and thus to reduce the siltation risk of the reservoir. The large control volume (0.2 hm^3) of the Granadino check-dam provides an ideal opportunity for continuous bedload monitoring in the study area. The objective of this study is to characterize bedload dynamics and its relationship with rainfall and snowmelt forcing agents by using field work conducted between January 2004 and March 2010 at the check-dam. For this study, hydrological modeling of the rainfall and snowmelt events has been combined with exhaustive field work to produce input for the different transport models used to estimate threshold entrainment and to study bedload dynamics. Specific focus has been placed on transport analysis, during significant selected events and throughout the entire silting period of the check-dam, to provide conclusions on the suitability of each model, with an emphasis on the importance of the mountainous conditions and snowmelt events in these semiarid environments.

2. Study site and available data

The Granadino check-dam is located along the main course of the Guadalfeo River (Fig. 1). The drainage basin covers an area of 485 km^2 and includes the northern and southern mountainous headwaters of the river and the eastern stretch of its main channel (length of 15 km and average slope of 0.011 mm^{-1}). The annual precipitation data show notable spatiotemporal gradients with average values of 460 and 630 mm y^{-1} in the valleys (<600–800 m asl) and mountain areas (>1500 m asl), respectively (Table 1), as well as periodic extreme events. At heights >2500 m, over 70% of the annual precipitation occurs as snow. The two mountainous headwater units present significant differences in terms of geology, geomorphology, and hydrology:

- The south side of the Sierra Nevada massif has a significant altitudinal gradient (300–3400 m), and the presence of snow from November to June determines the hydrological regime in this area. Runoff generation is to some extent delayed by the occurrence of intermediate snowmelt cycles that provide the streams with important delayed contributions such as base flow (Millares et al., 2009). The sediment contributions are characterized by moderate hillslope erosion rates (10–25 tn ha^{-1} y^{-1}) and nonrelevant bedload in the steep bedrock rivers in the area (Cádiar, Trevélez, and Poqueira rivers; Fig. 1).

Table 2

Main statistical descriptors of the annual precipitation (mm/y) corresponding to the 11 meteorological stations.

Station	Elevation (m asl)	Period	Mean precipitation	Standard deviation	Minimum precipitation	Maximum precipitation
Bérchules	1319	1946–2011	658	249	301	1617
Torvizcón	684	1946–2011	539	188	262	1265
Trevélez	1476	1946–2011	663	258	307	1635
Pórtugos	1120	1946–2011	726	286	326	1719
Soportújar	1700	1946–2011	692	261	336	1810
Órgiva	450	1946–2011	482	195	207	1434
Albuñol	1200	1946–2011	456	179	210	1026
Cádiar	950	1946–2011	429	186	218	1217
Tajos de Breca	2470	2005–2011	793	381	413	1474
Refugio de Poqueira	2510	2005–2011	829	379	434	1485
Contraviesa	1332	2005–2011	627	285	312	1062