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Sediment residence time in alluvial storage of black marl badlands

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ABSTRACT

The aim of this study is to estimate the sediment residence time in the stream network of two small headwater catchments (Laval and Moulin) characterized by a badlands landscape entrenched into Jurassic black marls of the Southern French Prealps. The method is based on an intensive field survey of the alluvial storage along the main stream reaches from which a scaling law between the average thickness of alluvial deposits and their width was established in order to predict the volume of alluvial deposits in the entire stream network. To complete this approach, bedload sediment yield monitored over the last 30 years with topographic surveying of sediment retention basins are used. The assessment of sediment residence time is performed according to a steady-state assumption, validated by the long-term dynamic equilibrium of bedload sediment yields. The results highlighted very close values of residence time between the catchments, around 3 years, despite a one order of magnitude difference in drainage area. It is shown that the rate of increase of alluvial storage with drainage area is the same as for sediment yield. This is likely attributed to the high degree of confinement of the stream network, which prevent the formation of a floodplain or large internal alluvial fans. Implications of these results for the prediction of the effects of bioengineering works in controlling erosion are discussed.

1. Introduction

In the Southern French Alps, black marls outcrops cover a large area. This geological formation is very susceptible to weathering and erosion (Antoine et al., 1995) and supply an important quantity of fine-grained sediments (silts and clays) to alpine rivers. Erosion rates measured in experimental catchments of Draix in the Bléone River basin over nearly 30 years are about 100 t ha^{-1} yr^{-1} with common suspended sediment concentrations (SSCs) exceeding several hundreds of g L^{-1} (Mathys et al., 2003). These erosion rates are among the highest in the Alps (Delannoy and Rovéra, 1996). Studies on sediment fingerprinting of the Bléone River basin revealed a significant contribution of black marls to the suspended sediment yield of the river; up to 70% for outcroppings representing only 10% of the drainage area (Navratil et al., 2012). In the Isábena River catchment in the Spanish central Pyrenees, the analysis of suspended sediment yield (SSY) by López-Tarazón et al. (2012) also highlights the major role of the marls outcrops (i.e., badlands) which are the main contributors in the suspended sediment yield of the catchment despite a very low surface area, only 1%. This very high suspended sediment load from badlands, often associated with water diversion for hydroelectricity, leads to river bed clogging and associated ecological impacts, as well as problems of reservoir sedimentation, like in the Durance River basin (Miramont et al., 1998; Warner, 2000). One possible solution to control the production of fine sediments from black marls badlands is to implement soil conservation programs, including the use of bioengineering techniques (Evette et al., 2009). In marly gullies of Draix, experiments are carried out to trap sediments upstream of vegetation barriers deployed in gully beds (Rey, 2005, 2009). Over one year, Rey (2005) showed that one brush barrier was able to trap an average of 0.11 m^3 and a maximum of 0.29 m^3, the trapped quantity increasing over time with vegetation growth. In Central Andean mountains, Molina et al. (2008) showed the major role of the vegetation cover in reducing sediment yields; for a 10–25% increase of the vegetation cover, a 60% decrease of the sediment yield was observed. The role of vegetation in reducing the connectivity of sediment transfer along a channel due to its influence on flow and sedimentation was also highlighted in the Cárcavo catchment (Sandercock et al., 2007; Sandercock and Hooke, 2011). In order to evaluate the efficiency of bioengineering works it is necessary to have a better understanding of sedimentary transfers. The longitudinal coupling does not always involve a continuous and regular transfer of flux, a delayed response being possible. Indeed, the sensitivity of a catchment to external changes is strongly controlled by the connectivity of its different geomorphic units (Hoffmann, 2015).

Since the emblematic Coon Creek sediment budget study of Trimble (1983) in Wisconsin, many investigations showed that upstream

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erosion control not always leads to the expected sediment response at the catchment outlet. On the Trinity River in Texas, Phillips et al. (2004) showed that the construction of a large dam in the upper basin did not reduced the sediment delivery downstream due to the buffering effect of the alluvial storage compensating sediment trapping from the dam. The same buffering effect from gravel storages is expected after the reforestation of active gullies in New Zealand North Island, even if a substantial decline of sediment supply from headwaters is documented following the restoration of a dense forest cover (Gomez et al., 2003). This buffering effect is especially important when the alluvial storage is high compared to the sediment flux passing through the geomorphic system, providing a convincing explanation for the stability of time-averaged sediment fluxes observed at different timescale (Métivier and Gaudemer, 1999). This has been formalized by the concept of sediment residence time, derived from the reservoir theory (Eriksson, 1971; Bolin and Rodhe, 1973). If a reservoir is in a steady state, it is demonstrated that the residence time can be defined as the ratio of the total mass in the reservoir to the total output flux. The residence time is therefore useful to evaluate the response of a system to a modification of the sediment supply upstream.

The documentation of sediment residence time in gully networks of black marls badlands is crucial for evaluating the likely effect of erosion control works. Because the gullies are narrow and steep it can be supposed that the alluvial storage is low, but the very high drainage density of gully networks may conversely contribute to store an important volume of sediment. This paper proposes to quantify the alluvial storage of the entire stream network in two small active badlands catchments of the Southern French Alps. The aims are to: (1) quantify the alluvial storage from field surveys and GIS spatial analysis, (2) evaluate the spatial distribution of alluvial storages, and (3) estimate the residence time of sediment in the stream networks.

2. Study sites

The Laval and Moulin catchments are part of the long-term black marls erosion observatory of Draix, where hydrology and sediment transport are monitored since the early 1980s (Mathys et al., 2003). They are located 15 km north-east of Digne-les-Bains, in the Alpes-de-Haute-Provence in France (Fig. 1). They drain into the Bouinenc Torrent, a tributary to the Bléone River. Elevations range between 850 and 1250 m and mean catchment slopes are 58 and 30% for the Laval and Moulin, respectively. They are also characterized by a high drainage density and a low vegetation cover (Table 1).

The geological formation is composed of Jurassic black marls from the Bajocian and Oxfordian periods. These muddy soft rocks are severely eroded by gullying processes, which results in typical V-shaped badlands morphology (Fig. 2). The climate is dominated by Mediterranean and mountainous influences. It is characterized by two rainy seasons (spring and autumn) and two dry seasons (summer and winter). Spring and autumn are generally characterized by long-duration and low-intensity rainfalls, while summer rainfalls are induced by high-intensity and short-duration convective storms. The annual rainfall is ~900 mm.

Exposed black marls are subject to mechanical weathering processes producing fine debris from few mm to few cm sized (Antoine et al., 1995). During winter, a several cm-thick weathered layer is forming on hillslopes under the effect of frost cracking (Mathys, 2006). These debris are depositing on footslopes by dry ravelling processes. Saturation of the weathered layer on steep slopes, especially at the end of winter during snow melt, may trigger shallow landslides and unconfined debris flows (Oostwoud Wijdenes and Ergenzinger, 1998; Yamakoshi et al., 2009). The very high sediment supply from hillslopes explain the ultra-high sediment transport rates observed at Draix, with fine sediment concentrations that can exceeds 600 $g\,L^{-1}$ during summer flash floods, and with specific sediment yields exceeding 10,000 $t\,km^{-2}\,yr^{-1}$ (Mathys, 2006).

The alluvial storage dynamics of the Laval and Moulin channels is characterized by seasonal cycles of erosion and deposition (Mathys, 2006). Channels fill during spring and summer, under the effect of the strong sediment supply from hillslopes, related to the accumulation of loose debris produced during winter and to the occurrence of heavy convective rainfall during the warm seasons. During autumn, the sediment supply from hillslopes is decreasing because most of the easily available loose debris has been removed, and because the rainfall intensity if insufficient to trigger erosion processes on hillslopes. As a consequence, a scouring of channel occurs during autumn and early winter (Fig. 3). Generally, the channel systems are dormant during winter.

3. Material and methods

3.1. Alluvial storage surveys

Alluvial storage surveys of the Moulin and Laval catchments were carried out in July 2007 and 2008, respectively. In total, 82 and 180 regularly-spaced cross sections were surveyed in the field along the Moulin and Laval stream networks, respectively (Fig. 4). The spacing between cross-sections was fixed at 5 m for the Moulin, at 15 m for the Laval main stream, and at 5–10 m for secondary links of the Laval stream network. These intervals were chosen as a compromise between the uncertainty level of sediment volume assessment and the labour cost of field surveys.

For each cross-section, the alluvial storage thickness was measured at 5 regularly-spaced intervals using a 1.45-m long rebar. The rebar was probed manually with a hammer in the alluvial layer up to the bedrock, and once the bedrock was reached, the sediment thickness was measured within 1-cm accuracy. A total number of 410 and 900 probes were done for the Moulin and Laval, respectively. For 8 probes in the Laval, the length of the rebar was insufficient to find the bedrock surface and it was not possible to measure directly the alluvial storage thickness. It was estimated indirectly by analysing the bedrock longitudinal profile along the concerned channel reach. During field surveys, the alluvial storage width was systematically measured for each cross-section, using a tape.

The total volume of the alluvial storage between two cross-sections i and j (V_{ij}) was obtained by:

$$V_{ij} = \left(\frac{(d_i \quad w_i) + (d_j \quad w_j)}{2}\right) L_{ij} \tag{1}$$

where d_i and d_j are the arithmetic mean of the alluvial storage thickness of cross sections i and j, respectively, w_i and w_j are the alluvial storage widths of cross sections i and j, respectively, and L_{ij} is the distance between cross-sections i and j.

3.2. Assessment of alluvial storage in the unsurveyed stream network

The evaluation of alluvial storage volume within the stream network that has not been surveyed in the field was made following a GIS and statistical approach. The network susceptible to support alluvial stores was manually extracted using a 0.5-m resolution slope map derived from an airborne LiDAR survey (Fig. 5). This slope map was used to identify alluvial flats along the stream network. Once the network was delineated, points were placed at a 5-m regular interval. For each point, the width of the alluvial flat was manually extracted from the slope map. For a width of one pixel, a width of 0.5 m was given. For a width greater than one pixel, a cross-section was traced to determine the width by calculating the distance between bank toes. Alluvial flat widths were used to predict alluvial storage thickness using an empirical scaling law derived from field data. This law is presented in the Results section.