Linkage between sediment transport and supply in mountain rivers

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Abstract

In this chapter, the issue of sediment supply and availability and its impact on sediment transport in mountain rivers is discussed, with some emphasis on high-magnitude low-frequency flood events. A review of field observations and modelling studies show that the amount and grain size of sediment transported by a flood of a given magnitude depend on flow competence and transport capacity but also on the characteristics of the sediment available for transport. The latter vary in space and time due to the episodic nature of the processes associated with sediment supply to channels and to variations in the nature of the sources (e.g., glacigenic sediment, soil or landslide; lithology of source rock). Change in the nature of sources can be driven by tectonics and climate through landscape steepness, the impact of glaciation and deglaciation, precipitation and storm intensity and/or the stabilising effect of vegetation. In steep landscapes, boulders up to a few meters in size are commonly supplied to channels and can inhibit sediment transport and bedrock erosion when abundant. Extreme flood events are crucial in mobilising the whole grain population, including boulders that can be considered stable over centennial to millennial time scales. Extreme floods can have either a depositing or a cleaning effect: the former occurs when substantial amount of excess sediment is supplied simultaneously to the event, leading to net aggradation; in the latter, the flood may flush all sediment available out of a given reach, leading to bedrock exposure and a sediment flux limited by sediment availability. The nature of the sediment exported from a reach or basin during extreme events will also depend on the time between events and on the time needed for in–channel sediment replenishment. These observations stress the need for integrating the sources of sediment and the episodic processes that lead to sediment supply to channels and sediment transport in channels when modelling sediment dynamics or bedrock erosion in mountain catchments, or the development of stratigraphy in sedimentary basins.

Keywords: sediment, erosion, transport, sediment sources, extreme floods, boulders, mountain rivers.

1.1 Introduction

Sediment transport in rivers occurs episodically during floods. In an ideal "transport limited" world (Willgoose et al. 1991) where the whole landscape would be made of loose sediment, sediment would always be available so the magnitude of a given flood would control sediment calibre (as a function of flow competence) and sediment flux (as a function of transport capacity), where sediment flux represents the amount of sediment transported by the river through a given reach per unit time. Such situation may arise in alluvial rivers but is not necessarily applicable to mountainous areas, where rivers tend to start their journey and where most of the clastic sediment is produced. Sediment in mountain rivers is supplied from hillslopes and rivers typically exhibit a mixed bedrock–alluvial morphology (Bathurst et al. 1986a, b; Howard et al. 1994; Turowski et al. 2008a). In such circumstances, sediment availability becomes crucial in controlling the amount of sediment that is transported during a given flow event, in particular for the most extreme events during which transport capacity may exceed sediment flux due to limited sediment availability (Howard et al. 1994; Wohl 2008; Morche and Schmidt 2012; Yager et al. 2012; Bennett et al. 2014). In this contribution, the issue of sediment supply and availability and its impact on sediment transport will be discussed, in particular with respect to high-magnitude low-frequency events.

Firstly, I review the evidence for the influence of sediment sources on the characteristics of the sediment available for transport in mountain rivers, in terms of grain size and lithological content. Field and modelling studies are used to illustrate the effect of spatial changes in source characteristics as well as episodic sediment supply to channels on the characteristics of the sediment available for transport. In section 3, I then discuss the impact of variable grain size and amount of sediment available in the channel (at the reach scale rather than at the bedform scale) on the characteristics of the sediment mobilised during floods of varying magnitude, with particular emphasis on the effect of boulders on sediment mobility and on the impact of extreme flood events.

1.2 Sediment supply to mountain rivers and its influence on the characteristics of the sediment available for fluvial transport

Shear stress applied on the river bed during a given flood event will control the transport capacity (e.g., Meyer–Peter and Müller 1948) and flow competence (e.g., Buffington and Montgomery 1997) at a given location. Total or partial sediment entrainment will occur depending on the grain size of sediment available in the river at the considered location; the amount of transportable sediment available will control whether the river will be "at capacity" or "under capacity" (Fig. 1). The grain size and volume of sediment available within the channel thus exert a key control on the grain size and volume of sediment exported during a flood event of a given magnitude (e.g., Yager et al. 2012; Bennett et al. 2014). These characteristics will vary both in space and time under the effect of abrasion and transport processes, but also in relation to the distribution of sources of sediment along the river. The relative importance of source characteristics (distribution of sources along the river, flux of sediment from sources, grain size, lithological content), abrasion and selective transport and deposition depends on the location along the river. In particular, a distinction can be made between upland areas ("mountains") and sedimentary basins (Fig. 2). In sedimentary basins, the supply of new fresh material to rivers is restricted to tributaries that may bring less "mature" sediment to the main stem river. The importance of sediment sources thus becomes negligible compared with the abrasion of sediment particles during transport events (floods) and selective transport and deposition that the predominantly depositional environment will promote (Paola et al. 1992; Fedele and Paola 2007). In the mountains, rivers primarily incise into bedrock and lower the base–level for hillslope erosion processes (Burbank et al., 1996). In such context, selective transport and deposition in the river are inoperative on the long term, since all the sediment supplied to the river is eventually evacuated from the mountain range (Attal and Lavé 2006). The characteristics and distribution of the sources of sediment and the abrasion of sediment particles during transport are thus the main control on fluvial sediment characteristics in upland areas. In the following sections, I review theoretical and field evidence for the influence of sources of sediment on spatial and temporal variations in the characteristics of the sediment available for transport in mountain (upland) rivers.

FIGURE 1

FIGURE 2

1.2.1 Spatial variations

Sources of sediment tend to be distributed along the course of rivers actively incising into bedrock (Fig. 2). Grains transported by rivers are reduced in size by abrasion, yet downstream fining is not necessarily observed, due to the sustained supply of fresh material (Heller et al. 2001; Attal and Lavé 2006; Sklar et al. 2006; Chatanantavet et al. 2010). For example, Attal and Lavé (2006) and Sklar et al. (2006) modelled the evolution of the grain size of fluvial sediment along a river flowing through a uniformly uplifted/eroded landscape in which hillslopes supply the same type of sediment: sediment supply was considered spatially uniform and the models assumed no net deposition. Both studies showed that the fluvial sediment grain size initially decreased before reaching an asymptote when the quantity lost by abrasion was counterbalanced by the supply of fresh material from the hillslopes. This phenomenon was documented along the Hoh River, Olympic peninsula, Washington, where no downstream fining was observed despite the high erodibility of the clasts which tend to develop thick, easily abraded, weathering rinds (Heller et al. 2001). Heller et al. (2001) concluded that "the continuous resupply of grains strongly attenuates the rate of downstream fining, despite the fact that these weathered grains abrade relatively rapidly".

Wolcott (1984) was one of the first to demonstrate the importance of the grain size distribution of sediment sources in setting the grain size distribution of the sediment transported by rivers. Wolcott compared the grain size of fluvial sediment in two catchments in Oregon with the grain size of the sources of sediment for the rivers (hillslopes, bars and channel banks). He showed that the grain size of the sources of sediment was influenced by the lithology of the underlying rocks: the weathering of sandstones and siltstones produced sediment with a bimodal grain size distribution, in contrast to basalt–derived sediment which exhibited a unimodal grain size distribution. The grain size distribution of the sediment transported by rivers was found to be bimodal in the basin underlain by sandstones and siltstones and unimodal in the basin underlain by basalt (Wolcott 1984). Attal and Lavé (2006) also found that rock type influences the characteristics of the sediment at the source along the Marsyandi River (Himalayas): landslides in quartzite and gneiss supply coarser sediment than landslides in schist, with median grain size D_{50} in the ranges 18–74 mm and 3–23 mm, respectively. Marshall and Sklar (2012) further found a relationship between abundance of rock fragment in soils and climate. In particular, higher precipitation rate was found to correlate with lower rock fragment abundance and reduced occurrence of bimodal size distributions across sites spanning a range of environmental conditions in the Hawaiian islands, the Sierra Nevada (California) and Cascade Mountains (Washington) (Marshall and Sklar 2012).

The type of rock supplied to the fluvial system also influences fluvial sediment characteristics through differences in rock resistance to abrasion, which govern how quickly each sediment particle is reduced in size. In areas where rocks of different lithologies are supplied to rivers, the most resistant lithologies (e.g., granite, quartzite, volcanics) end up being overrepresented in the bedload compared with the least resistant lithologies (e.g., schist, sandstone) which are rapidly reduced in size (e.g., Mezaki and Yabiku 1984; Parker 1991; Attal and Lavé 2006, 2009). The grain size and amount of sediment available for transport is therefore strongly controlled by the relative contribution of the different rock types within the catchment, with the most resistant lithologies such as quartzite likely to dominate the coarser fraction (cobble, boulders) whereas the least resistant lithologies will contribute essentially to the finest fractions (gravel, sand and suspended load) (Attal and Lavé 2006, 2009).

The introduction in the river of sediment with distinct characteristics from a point source tends to have a local effect on fluvial sediment that dissipates downstream (Sklar et al. 2006). On the other hand, when the change in sediment supplied to the river is sustained, theoretical (Sklar et al. 2006) and field studies (Attal and Lavé 2006; Whittaker et al. 2008, 2010; Attal et al. 2015) have shown that the characteristics of the fluvial sediment can be significantly affected. The field studies showed that the median grain size D_{50} and 84th percentile D_{84} of fluvial sediment increased significantly both on the surface and in the subsurface in response to a coarsening of sediment sources (Fig. 3). In these cases, change in the grain size of sediment sources was not due to a change in lithology but to a change in the process that generates sediment: the coarsening was associated with a change either from predominantly glacially–derived to landslide–derived sediment (Attal and Lavé 2006) or from soil–derived to landslide–derived sediment (Whittaker et al. 2008, 2010; Attal et al. 2015). The increase in fluvial sediment grain size was spatially coincident with the change in sediment source, suggesting an immediate response of fluvial sediment characteristics to changes in source characteristics.

FIGURE 3

1.2.2 Temporal variations

Sediment supply to rivers tends to be an episodic process due to the episodic nature of the triggers: sediment will be supplied to rivers via landslides, debris flows, dry ravel or bank collapse following storms, earthquakes, wildfires, snowmelt and/or rising river stage (e.g., Bathurst et al. 1986a, b; Benda and Dunne 1997; Gabet 2003; Dadson et al. 2003, 2004; Lancaster 2008; Yanites et al. 2010; Singer et al. 2013; Bennett et al. 2014). As a result, the availability of sediment in a given river reach can significantly change through time, depending on the magnitude of the disturbance (the trigger) and its recurrence interval. Point sources (e.g., isolated landslide) tend to cause pulses of sediment with a signature that reflects the type and magnitude of the supply process; these pulses tend to dissipate downstream due to the diffusive nature of the sediment transport process (Benda and Dunne 1997; Cui et al. 2003a, b; Sklar et al. 2006). In addition to sediment transport, temporary storage in channels (e.g., in floodplains) can also buffer the pulse–like nature of sediment supply (e.g., Métivier and Gaudemer 1999; Phillips 2003; Lancaster 2008; Blöthe and Korup 2013). The influence of sources on temporal variations in sediment availability and characteristics (e.g., grain size) will therefore be greatest in low order streams or when the supply events are of high-magnitude. I present below a few examples to illustrate these points.

Death Valley (California) is bordered by numerous small catchments with well–developed alluvial fans. Channels tend to be entrenched in fan surfaces dating from the Pleistocene (Dorn 1996). Mosaic Canyon drains one of these small catchments (~11 km^2) on the western side of Death Valley (Fig. 4). The main lithologies exposed in the catchment are white marble and black schist. As the river incises into its alluvial fan, it exposes strata with very different characteristics. In particular, the succession includes beds with up to 95 % very angular marble clasts with median grain size ~3–4 cm alternating with beds with up to 95 % sub–rounded schist clasts with median grain size ~1 cm (Fig. 4). The most logical explanation for this observation is a source effect, whereby sediment availability in the basin is dominated by point sources such as landslides: fluvial transport events that led to the formation of the schist–dominated or marble–dominated beds would have occurred following supply events that led to the availability of either easily abraded schist or comparatively resistant marble, respectively.

FIGURE 4

A similar observation was made by Attal and Lavé (2006) in a much larger basin. At Chame, around 50 km downstream of the source of the Marsyandi River (Himalayas), the contributing drainage area is 680 km^2. The rocks in the contributing area are essentially schists and limestones from the Tethyan Series, with the gneiss from the Higher Himalayan Crystalline representing a few percent of the contributing area (Attal and Lavé 2006). Yet, the fraction coarser than 4 cm in modern gravel bars is made of nearly 40 % of gneiss; in the vicinity, terrace deposits contain nearly 100 % limestone clasts (Attal and Lavé 2006). This observation suggests a significant recent supply of gneiss upstream of Chame, possibly associated with landslides. Similar observations were made in the tributaries Naur and Dudh Khola which join the Marsyandi River downstream of Chame.

Most sources of sediment for rivers tend to be point sources rather than diffuse. However, external factors can cause generalised supply by point sources at a basin scale. Lane et al. (2008) showed that coarse sediment supply from hillslopes and tributaries to the Upper Wharfe, an upland river in the Yorkshire Dales (UK), tends to happen following powerful storms, irrelevant of the antecedent conditions (dry or wet); these events typically happened as a result of convective storms in summer, demonstrating a seasonal control on sediment supply to the channel in this context. Major external disturbances can also trigger widespread sediment supply over a given area. Dadson et al. (2003, 2004) and Yanites et al. (2010) show a strong link between sediment supply to rivers in Taiwan and both storm intensity and ground shaking during earthquakes. Yanites et al. (2010) estimated that the magnitude 7.6 Chi–Chi earthquake in Central Taiwan and subsequent Typhoon Toraji in 2001 caused 50000 landslides within a 3000 km^2 region. Within this region, Yanites et al. (2010) made a rough estimate of the amount of debris produced of ~0.5–1.3 × 10^4 Mt, "equivalent to stripping ~0.6–1.7 m of material off the landscape" (Yanites et al. 2010). This extraordinary "pulse" of sediment caused widespread aggradation in the rivers in the area, with up to 18 m vertical aggradation in places. On a larger scale, Pratt–Sitaula et al. (2004) document widespread aggradation in excess of 100 m in the Marsyandi Valley, Himalayas. They date two aggradation phases at 50–35 ky and ~8 ky BP, that they interpret as resulting from monsoon intensification. The shift to wetter conditions would have caused widespread hillslope destabilisation, supplying a considerable amount of sediment that takes thousands of year to be evacuated.

1.3 Influence of varying sediment availability on sediment transport and export during floods

In section 2, I reviewed evidence for the influence of sources on the availability and characteristics (grain size, amount, lithological content) of sediment in mountain rivers. In this section, I discuss the influence of spatial and temporal variations in sediment availability and characteristics on sediment transport during flood events of varied magnitude, including extreme events.

1.3.1 Geomorphic work as a result of the interplay between flood magnitude and sediment supply

Because sediment availability can be limited in mixed bedrock–alluvial mountain rivers, the largest floods are not necessarily associated with the greatest amount of sediment transported. Instead, floods of different magnitudes will do different type of geomorphic work depending on whether sediment is readily available and whether threshold for entrainment is overcome (Bathurst et al. 1986a, b; Costa and O'Connor 1995; Wohl 2008; Yager et al. 2012; Bennett et al. 2014). Lane et al. (2008) observed for example a dichotomy in the effects of short–lived, high intensity storm events and longer–lived, moderate storm events on sediment dynamics in the Upper Wharfe catchment (Yorkshire Dales, UK). They found that sediment supply to tributaries and main channel tends to occur as a result of short periods of intense rainfall, typically in summer. During such events, they documented limited sediment transport in the main channel that they link to the short duration of the events; sediment transport in the main channel was essentially happening in winter, following moderate events that were able to sustain sediment transport for longer.

In mountain rivers, sediment aggradation can lead to the development of alluvial planform patterns (such as braiding or meandering) within a system constrained by bedrock. This "alluvial overprint" (Carling 2009; Meshkova and Carling 2012; Meshkova et al. 2012; Turowski et al. 2013) can influence sediment dynamics in response to floods of different magnitude. Turowski et al. (2013) document two contrasted behaviour that they call "flood–depositing" and "flood–cleaning", which may be conceptualised by a model in which sediment supply to a given reach Q_s is a power function of water discharge Q (Turowski 2012):

$$Q_s = cQ^{\lambda} \quad (1),$$

where c and λ are constants. The “flood-depositing” case corresponds to $\lambda > 1$; in this case, low–frequency high–magnitude floods supply more sediment than they can evacuate, leading to significant sediment deposition within the reach in question. Sediment is subsequently progressively evacuated through time during small and moderate floods. In the “flood-cleaning” case ($\lambda < 1$), sediment progressively builds up in the channel following high–frequency low–magnitude events; an extreme event then flushes a significant part or all of the sediment out of the reach. Turowski et al. (2013) review evidence from the literature and report that both behaviours are observed in both bedrock and alluvial rivers. They also show that the dominant behaviour can change spatially and potentially in time within a single basin, with some large basins (Clyde River, Australia (Nanson 1986) and Sabie River, South Africa (Heritage et al. 2004)) exhibiting alternating flood–cleaning and flood–depositing reaches. In fact, they link the two behaviours to channel–hillslope coupling, inferring that sediment must be supplied from hillslopes during aggrading phases, that is, during high-magnitude events in flood–depositing streams and during small and moderate floods in flood–cleaning streams. The relative timing of floods and sediment supply to the channel is therefore crucial in controlling the amount of sediment transported in a given reach and exported from a basin during floods of varying magnitudes (Bathurst et al. 1986a, b).

It is notable that following major disturbances such as the ones documented in Taiwan (Dadson et al. 2003, 2004; Yanites et al. 2010) or along the Marsyandi River in the Himalayas (Pratt–Sitaula et al. 2004) (section 2.2), sediment availability will not limit sediment transport even for extreme events for a significant amount of time, due to the colossal nature of vertical sediment aggradation within the valleys, from tens to in excess of a hundred meters. Pratt–Sitaula et al. (2004) and Yanites et al. (2010) estimate the time for evacuation of sediment to be in the order of hundreds to thousands of years. During this period, rivers are likely to be “at capacity” during floods, the main constraint on sediment entrainment being the need to overcome the threshold for incipient sediment motion. These basin–scale alluviation events are typically associated with generalised slope instability and landsliding (Dadson et al. 2003, 2004; Pratt–Sitaula et al. 2004; Yanites et al. 2010), leading to a wide range of sediment grain sizes being supplied to the river, up to boulders a few meters in size (Attal and Lavé 2006; Whittaker et al. 2008, 2010; Attal et al. 2015) that may be mobilised only during the most extreme events. The coarseness of sediment present in the channel may therefore act as the main inhibitor of sediment transport (e.g., Wohl 1992; Jansen 2006), which will be discussed in the following section. The generalised destabilisation of hillslopes may temporarily exhaust the sources of sediment; regeneration of sediment on hillslopes (e.g., soil development) would be possible during the hundreds to thousands of years that the river will need to evacuate the valley fill.

1.3.2 Grain size and sediment mobility: the boulder issue

As mentioned in section 2 (Fig. 1), the maximum grain size of the sediment entrained during a flood will be limited either by the grain size of the sediment available for transport (if sediment available is relatively fine–grained with respect to flow competence) or by flow competence (if a wide range of grain sizes is available, up to boulder size). The coarseness of the sediment supplied to rivers can therefore exert an important control on the grain size of the sediment transported during a given flood: a very powerful flood will not be able to transport coarse sediment if no coarse sediment is available for transport. Such a situation may arise in low relief, soil–mantled landscapes (Fig. 3b, c, e) (Whittaker et al. 2008, 2010; Attal et al. 2015) or where large amounts of sediment lacking large clasts is available within a catchment (e.g., badlands or conglomeratic bedrock, e.g., Mather and Hartley (2005)). In other types of mountainous landscapes, sediment available for transport is likely to include large clasts up to boulder size supplied by landslides, debris flows or rock falls, or left behind by glaciers (e.g., Chatanantavet et al. 2010; Attal et al. 2015).

In mountain rivers, boulders can contribute to the development of bedforms that tend to limit the mobility of the sediment as a whole. Many studies have documented the formation of step-pool morphology in the presence of boulders, in particular where the size of bed materials is large relative to the channel size (see reviews on the topic by Chin and Wohl 2005; Church and Zimmermann 2007; Comiti and Mao 2012). The formation of steps is associated with the largest clasts acting as anchor points against which other clasts become imbricated and stop moving. The steps are therefore made of a variety of clast sizes, with the boulders acting as keystones. Moderate floods tend to maintain this morphology by contributing to the scouring of the pools upstream of steps, whereas high-magnitude low-frequency events are able to destroy the steps and mobilise the sediment “frozen” in the steps and between them (e.g., Gintz et al. 1996; Lenzi et al. 2004, 2006; Church and Zimmermann 2007; Wohl 2008; Turowski et al. 2009, 2013; Morche and Schmidt 2012; Yager et al. 2012). In the case of isolated boulders, a series of approaches have been proposed to estimate the magnitude of the flood capable of setting a clast of a given size in motion (e.g., Clarke 1996; Carling and Tinkler 1998; Carling et al. 2002a, b; Stokes et al. 2012). The different methods have been shown to produce significantly different results (see discussion in Stokes et al. 2012) but they can be used nevertheless to give a rough estimate of the flow depth required to mobilise a boulder of a given size. Using the equation described in Stokes et al. (2012) with the same values of fluid and boulder density and the same values of lift, drag and sliding coefficients, the following flow depths for incipient motion were found:

in a channel with a slope ranging between 0.1 and 0.01 (which is typical of mountain rivers), the flood that would entrain 0.5 and 1 m diameter boulders would have a minimum depth ranging between 0.9 and 1.8 and between 1.5 and 3.0 m, respectively. Abundant and/or large boulders may therefore be considered as a potentially significant hindrance to sediment entrainment during floods (e.g., Wohl 1992; Yager et al. 2007), in particular in the least steep reaches of mountain rivers.

Beyond the bedform scale, a few studies have provided evidence for the influence of boulders on channel geometry, that were linked to reduced sediment mobility and bed armouring. Howard et al. (1994) argue that boulders sourced locally from the walls of the Grand Canyon (Colorado) reduce alluvium mobility and therefore river incision, causing a negative feedback: rapid incision generates deep narrow gorges from the walls of which boulders will be produced, which will then inhibit river incision. Brocard and van der Beek (2006) and Johnson et al. (2009) both document significant channel steepening in response to local supply of boulders along actively incising rivers. Johnson et al. (2009) document differences in the geometry of channels incising into similar sandstones in the Henry Mountains (Utah): channels that have abundant large diorite clasts (cobbles, boulders) sourced from localised exposures in the headwaters are less incised and steeper than channels with no diorite clasts. They propose that the cover effect provided by the not very mobile coarse sediment inhibits incision and that the steepening would represent a long–term response of the channel to transport the sediment load (evidence for the transport of the diorite clasts exist in the form of imbrication and boulder jams). Brocard and van der Beek (2006) show that the local supply of large boulders from limestone cliffs causes a steepening of rivers incising into marls in the Western Alps (SE France) (their Fig. 5). They argue that the boulders are too large to be transported by the river and that the armouring caused by abundant boulders would effectively be equivalent to limestone bedrock. Clarke and Hansen (1996) made similar observation of “extremely stable boulders” that are unlikely to be entrained under the current climatic regime in small basins in an arid environment in California (Anza Borrego Desert). This effect could literally be called “bedrock aggradation”: the river will need to abrade or break the boulders into fragments of smaller size before entrainment could happen and the river could incise into the underlying bedrock. As in Johnson et al. (2009), Brocard and van der Beek interpret the local steepening as a long–term response of the channel to provide the extra work required to deal with the boulders. “Bedrock aggradation” in the form of very large boulders in channels is widespread in steep landscapes (Fig. 5) and tends to cause channel adjustment because only infrequent extreme flood events would be able to mobilise them, as discussed in the next section.

FIGURE 5

1.3.3 Sediment transport during extreme flood events

Extreme floods are exceptional events with recurrence intervals typically exceeding a century, that are capable of transporting very coarse sediment in colossal quantities, cause significant bedrock erosion and therefore produce major landscape change (e.g., Baker 1978; Wohl 1992; Baker and Kale 1998; Montgomery et al. 2004; Gupta et al. 2007; Garcia–Castellanos et al. 2009; Warner et al. 2010; Baynes et al. 2015). Such events can be caused by powerful storms or typhoons, landslide dam break, glacial lake outburst or subglacial volcanic eruptions; whereas some of these causes will be restricted to some area (e.g., subglacial volcanic eruptions), others will be common over geological time scales in mountainous landscapes (e.g., landslide dam breaks).

Extreme events may have the ability of mobilising the entire grain population, leading to full mobility even in the presence of very large boulders. Evidence for transport of boulders up to a few meters in size during extreme floods abounds in the literature (e.g., Williams 1983; Beaty 1989; Baker and Kale 1998; Wohl 1992; Carrivick et al. 2004; Mather and Hartley 2005; Lamb et al. 2008; Carling et al. 2009, 2013; Marren et al. 2009; Russell et al. 2010; Stokes et al. 2012), although hyperconcentrated or debris-flow processes rather than fluvial processes may have been involved in some of these cases (e.g., Mather and Hartley 2005). Extreme floods therefore play a crucial role in transporting sediment that could be considered stable over centennial to millennial time scales, due to their coarseness and/or the development of resistant bedforms such as armoured layers or pools and riffles (e.g.; Wohl 1992, 2008; Lisle and Church 2002; Jansen 2006; Yager et al. 2007; Turowski et al. 2009, 2013; Baggs Sargood et al. 2015). The size of the largest clasts transported during such events may be limited by the coarseness of sediment available for transport (Mather and Hartley 2005).

In terms of sediment flux, such extreme events are likely to result in net sediment export from the mountain area to areas downstream where transport capacity is significantly reduced, typically as a result of slope reduction and/or channel/valley widening (e.g., sedimentary basin, Fig., 2) (e.g., Carling 2013). At the reach scale, the flood will not necessarily have a “cleansing” effect in the mountainous reaches in the sense that bedrock will not necessarily be subsequently exposed. Figure 6 schematically represents different scenarios based on the initial amount of sediment present in the channel and whether the reach considered behaves in a “flood–depositing” or “flood–cleaning” way (Turowski et al. 2013). The volume of sediment exported from the reach will be limited by transport capacity if considerable amounts of sediment are present in the channel before the flood (e.g., following a phase of generalised aggradation – Fig. 6a) (e.g., Pratt–Sitaula et al. 2004) and/or if the reach is behaving in a flood–depositing way (Fig. 6). Turowski et al. (2013) give examples of flood–depositing reaches where low–frequency high–magnitude floods lead to aggradation, which they interpret as a result of synchronous excess sediment supply from hillslopes; the Taiwan example discussed in previous sections exemplifies this behaviour. Note that in this discussion I focus on the net effect of given flood: it is interesting to note that during an event, a flood may be depositing at low discharge, eroding at high discharge, and depositing again at low discharge. Whether this results in net aggradation or erosion depends on the dependence of the transport capacity on discharge, sediment availability and the shape of the hydrograph (e.g., Rickenmann 1997).

FIGURE 6

Sediment flux will be limited by sediment availability if the reach is behaving in a flood–cleaning way and the initial volume of sediment in the channel is limited (Fig. 6b, c). In such situations, the extreme flood will have a cleansing effect, flushing out sediment and exposing bedrock (see example in Fig. 7) (e.g., Wohl 1992; Jansen 2006; Turowski et al. 2013; Baggs Sargood et al. 2015). Subsequent floods of any magnitude are likely to have limited sediment flux for the time needed to replenish the stock of sediment available for transport within the channel. The time between floods is therefore crucial in controlling the geomorphic response and amount of sediment that will be exported by a flood of a given magnitude (Harvey 1984; Cenderelli and Wohl 2003; Wohl 2008). Regarding extreme floods, the effect of this "replenishment time" may be considerable both for the amount and type of sediment that will be exported from a catchment, due to the fact that extreme flood events can also lead to significant bedrock erosion. I present a simple model in Figure 8 that illustrates the potential effect of sediment exhaustion and recurrence time of extreme floods on the flux and type of sediment exported. The model describes the origin and volume of sediment exported from a given river section during extreme events as a function of the time between events (relative to the time needed for sediment replenishment in the channel). The model stresses that sediment exported during two extreme events of similar magnitude may represent very different volumes and include very different proportions of material sourced from bedrock, depending on the time between events, bedrock resistance to erosion and the necessity for tools to detach bedrock. As a result, the two events of similar magnitude may export sediment with very contrasted characteristics (volume, lithological content, roundness of clasts, grain size distribution), with bedrock constituting a local source of likely angular sediment lacking fines (< sand size). This behaviour exemplifies the need to understand the internal dynamics of river basins before interpreting changes in sedimentary successions in terms of tectonics or climatic signals, as autogenic processes and bed reorganisation can lead to the shredding of environmental signals (e.g., van de Wiel and Coulthard 2010; Jerolmack and Paola 2010).

FIGURE 7
FIGURE 8

Hartshorn et al. (2002) document a possible feedback mechanism between extreme events and sediment replenishment. They show that an extreme flood event along the Liwu River in Taiwan during the powerful typhoon Billis in 2000 (maximum flow depth = 12 m) caused considerable bedrock erosion. However, erosion peaked on the banks of the channel, a few meters above the mean low–flow level. They concluded that in the studied channel, bed lowering is driven by moderate flood events whereas extreme events tend to widen the channel and therefore transmit the erosion signal to the hillslopes. The undercutting of the hillslopes by an extreme flood may cause widespread destabilisation and generalised mass movement and therefore increased sediment supply and replenishment to the channel (see also Hovius and Stark 2006; Turowski et al. 2008b; Turowski 2012). Morche and Schmidt (2012) provide evidence for such an effect: following a landslide dam break along the Partnach River (Bavarian Alps), field observations and monitoring of water and sediment transport along the river show a sustained increase in the bedload contribution, that the authors interpret as partly resulting from the re–coupling of the channel with hillslopes downstream of the dam. They observed that the outburst flood cut the feet of several talus cones and measured elevated transport rates, in particular for bedload, that were sustained for four years after the event (see also Gintz et al. 1996; Lenzi et al. 2004; Turowski et al. 2009).

An extreme flood is likely to cause considerable sediment transport and therefore considerable sediment deposition at the end of the flood (e.g., Carling 2013). Sediment will be deposited where the flow loses power, for example where the valley widens such as at the transition from the confined channel to the sedimentary basin (Fig. 2) or at the coast (e.g., Russell et al. 2010). Widespread deposition will also happen at the end of the flood. At a local scale, flow constrictions, valley widening, slope reduction, plunge pools at cataracts and bends may reduce stream power (e.g., backwater effect) and cause sediment deposition, even within the mountainous realm (e.g., Wohl 1992; Meshkova and Carling 2012). The extreme event may have opposing effects on the mobility of in–channel sediment for subsequent, potentially smaller floods. Mobility may be increased through the destruction of resistant bedforms and displacement or removal of boulders (Lenzi et al. 2004, 2006; Wohl 2008; Turowski et al. 2009, 2013; Morche and Schmidt 2012); for example, Lenzi et al. (2004) document increased bedload transport for floods of a given magnitude following a large flood in an Alpine catchment. However, the event may also result in the formation of boulder bars that will be stable until the next extreme event or until the blocks are reduced in size by abrasion (e.g., Wohl 1992; Jansen 2006; Baggs Sargood et al. 2015).

1.4 Concluding remarks

In mountain rivers, the amount and grain size of sediment transported by a flood of a given magnitude depend on flow competence and transport capacity but also on the characteristics of the sediment available for transport. The latter vary in space and time due to the episodic nature of the sediment supply processes and to variations in the nature of the sources (e.g., glacigenic sediment, soil or landslide; lithology of source rock). Change in the nature of sources can be driven by tectonics and climate through landscape steepness, the impact of glaciation and deglaciation, precipitation and storm intensity and/or the stabilising effect of vegetation. A spatial or temporal change in tectonics or climate may therefore influence the type and amount of sediment supplied to mountain rivers, which should be reflected in the characteristics of the sediment transported by rivers and exported to sedimentary basins.

In steep landscapes, boulders up to a few meters in size are commonly supplied to channels and can inhibit sediment transport and bedrock erosion when abundant. Extreme flood events are crucial in mobilising the whole grain population, including boulders that can be considered stable over centennial to millennial time scales. Extreme floods can have either a depositing or a cleaning effect (Turowski et al. 2013): the former occurs when substantial amount of excess sediment are supplied simultaneously to the event, leading to net aggradation; in the latter, the flood may flush all sediment available out of a given reach, leading to bedrock exposure and a sediment flux limited by sediment availability. The nature of the sediment exported from a reach or basin during extreme events will also depend on the time between events and on the time needed for in–channel sediment replenishment. Because extreme events can flush sediment out of a reach, transport (and deposit) large boulders and erode bedrock, they can have a long–lasting legacy on sediment storage and mobility in a given reach. These observations stress the need for integrating the sources of sediment and the episodic processes that lead to sediment supply to channels and sediment transport in channels when modelling sediment dynamics or bedrock erosion in mountain catchments, or the development of stratigraphy in sedimentary basins (Walling 1983; Yager et al. 2012; Turowski et al. 2013; Bennett et al. 2014).

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1.6 References

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Figure caption

Figure 1: Schematic illustration of the interplay between flow competence, transport capacity, amount and grain size of sediment available for transport, and the properties of the sediment exported from a given mixed bedrock–alluvial reach during a flood event. Grey box at the top is a schematic representation of the amount of sediment the river can transport out of the reach at the time considered (transport capacity – black rectangle is a size guide in all diagrams); the maximum grain size entrained at that time is shown in the box (flow competence). The four diagrams show the reach considered (delineated by the bold dashed lines) in different situations. In the left diagrams, the sediment available is finer than what the river can transport, leading to full mobility. In the right diagrams, some grains are larger than what the river can transport (dark grains), leading to partial transport (e.g., Wilcock and McArdell 1997). Top and bottom panels illustrate "at capacity" and "under–capacity" scenarios, respectively, resulting from (im)balance between the amount of sediment available for transport and transport capacity. Note that this figure is based on a very simplistic model where the river transports all the grains that are smaller than a given size; it ignores factors that can decrease the mobility of the sediment mixture as a whole, such as the armouring effect, clast interlocking and/or a large proportion of large clasts (e.g., Lisle and Church 2002).

Figure 2: Schematic depicting the fate of sediment particles from upland areas to sedimentary basins. Note that this diagram presents a situation that typically arises in tectonically active areas, with a sharp transition from (uplifted) mountainous area to (subsiding) sedimentary basins; the transition will be more subdued in tectonically quiescent areas. Upstream of the mountain front, sediment particles are progressively reduced in size by abrasion as they are transported downstream; selective transport and deposition are inoperative on the long–term since all sediment supplied to the river is eventually evacuated from the mountain range; supply of fresh material from hillslopes (e.g., landslides "L") and tributaries all along the river course can prevent downstream fining. Downstream of the mountain front, the depositional environment and the absence of fresh sediment supply leads

to downstream fining under the combined effects of selective transport and deposition and sediment particle abrasion during fluvial transport.

Figure 3: (a), (b) and (c): fluvial sediment grain size as a function of distance downstream along three rivers exhibiting prominent changes in source type (note change in scale on x and y axes). (a): the increase in grain size along the Marsyandi River coincides with a change in source type from glacial till (D_{50} = 6–24 mm) to landslide–derived sediment (D_{50} = 3–74 mm) (adapted from Attal and Lavé 2006). (b): in response to an increase in fault throw rate, the landscape steepened upstream of the Fucino fault (Celano Gorge). Increase in fluvial sediment grain size coincides with the transition from low–relief landscape (source of sediment = soil) to steepened landscape (source of sediment = scree cones and landslides) (adapted from Whittaker et al. 2010). (c): the situation in Adams Creek is very similar to (b), except that the steepening is caused by rapid incision of the Feather River of which Adams Creek is a tributary. Fluvial sediment coarsening is observed at the transition from low–relief landscape (source of sediment = soil, D_{50} = 0.1–1.2 mm) to steepened landscape (source of sediment = scree cones and landslides, D_{50} = 35–66 mm) (adapted from Attal et al. 2015). (d), (e) and (f): pictures illustrating the different domains. (d): Marsyandi River tapping into glacial sediment. (e): soil–mantled hillslopes in low–relief landscape in the Apennines. (f): Steepened landscape along the Feather River, Sierra Nevada.

Figure 4: Mosaic Canyon, Death Valley, California. (a): location of Mosaic Canyon (Imagery ©2015 DigitalGlobe, Landsat, USDA Farm Service Agency, Map data ©2015 Google). (b) and (c): Quaternary fan sedimentary succession exposed near the mouth of the catchment following entrenchment, looking upstream and downstream, respectively. The succession includes beds with contrasted grain size, grain angularity and lithological content. (d): detail of two successive beds: the lower bed has around 95 % sub–rounded schist clasts with median grain size ~1 cm, whereas the upper bed has around 95 % very angular marble clasts with median grain size ~3–4 cm.

Figure 5: Examples of large boulder concentrations inhibiting bedrock erosion along actively incising rivers. Where concentration of boulders a few meters in size is high, their effect may be compared with “bedrock aggradation”. Boulders typically exhibit fluting and potholing, testifying to their low mobility; only extreme floods may move them. (a) and (b): general view and close up of the Feather River, California, where it incises into the Bald Rock granitic pluton (adapted from Attal et al. 2015). River is ~30 m wide; it flows towards bottom right corner of picture in (a) and towards camera in (b). Person is circled in (b) for scale. (c): Marsyandi River, Himalayas, where it incises into the silicified Annapurna limestone

downstream of Pisang (Nepal); channel is ~20 m wide and river flows towards camera. (d): large gneiss boulder in Marsyandi River showing intense fluting and potholing on its lee side (picture taken from above, arrow indicates flow direction). Abrasion by suspended and bedload is effective during floods, when the boulder is submerged. Over time, abrasion can efficiently reduce the size of boulders, potentially to a size that may be mobilised during a moderate flood.

Figure 6: Schematic evolution of valley fill following an extreme flood, considering three different initial conditions and depending on whether the reach is "flood–depositing" or "flood–cleaning" according to Turowski et al.'s (2013) model. In (a), the flood is not powerful enough to mobilise all sediment in the reach and bedrock is not exposed. In (b) and (c), all sediment is mobilised in the reach; little or no sediment is preserved in the channel following the flood in the flood–cleaning scenario. Note that bedrock erosion is likely to happen in all (b) and (c) scenarios and may therefore contribute to the sediment load; in the flood–depositing case in (b), bedrock is not exposed before or after the flood but sediment moves and interacts with the bedrock during the flood ("dynamic cover effect" (Turowski et al. 2007)), likely leading to significant bedrock erosion. Dashed line on the diagrams to the right represents pre–flood sediment level. Changes in channel shape due to bedrock erosion are not represented.

Figure 7: Evidence for the impact of extreme floods along the Jökulsá a Fjöllum, NE Iceland. (a): satellite image (Imagery ©2015 Cnes/Spot Image, DigitalGlobe, Map data ©2015 Google) showing the scablands around the Dettifoss waterfall. B and C show the location of the pictures (b) and (c), respectively. Dashed lines delineate thick glacial sediment deposits. One or more extreme flood event(s) cleared the glacial sediment along the path illustrated by the large arrows during the Holocene, exposing basalt bedrock (Baynes et al. 2015). (b): glacial sediment, palaeo–flood channel and sediment "island" in the background. (c): exposed bedrock in the path of the palaeo–flood. If a new extreme flood follows the same flow path, sediment in this area will be essentially sourced from bedrock erosion.

Figure 8: Simple model of sediment transport and bedrock erosion during extreme events. Here, two large single events of similar magnitude occur during the time considered. These events have the capacity to flush sediment out of the considered river section and cause bedrock erosion. In (a), the second flood occurs after sediment has replenished in the channel and the amount and type of sediment exported is similar to during the first flood. In (b), the second flood occurs very shortly after the first one and the sediment is essentially sourced from bedrock erosion. Different scenarios can be envisaged: (1) bedrock is highly

erodible and the amount eroded is limited by transport capacity; (2) bedrock erosion is limited by the availability of material that can be detached, e.g., blocks that can be plucked from bedrock due to open joints and cracks in the near subsurface (e.g., Whipple et al. 2000); (3) bedrock erosion is inhibited by the lack of tools for erosion by abrasion and/or plucking (Whipple et al. 2000; Sklar and Dietrich 2001). Note that this model does not make any assumption regarding the mechanisms that lead to sediment replenishment and whether replenishment is progressive or episodic. It just assumes that a given amount of time is needed for sediment availability in the channel to equate sediment availability before the first flood.