Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006.

Episodic discharge of coarse sediment in a mountain torrent

RICHARD JOHNSON[1] & JEFF WARBURTON[2]

1 *School of Natural Resources, University of Central Lancashire, Penrith Campus, Penrith, Cumbria CA11 0AH, UK*
rmjohnson1@uclan.ac.uk

2 *Catchment, Hillslope and River Science Research Group, Department of Geography, Durham University, Science Laboratories, South Road, Durham DH1 3LE, UK*

Abstract Direct observations of coarse sediment transport in mountain streams are rare. This paper describes a unique, high resolution record of coarse sediment flux from a steep, mountain torrent in the English Lake District, UK. A recording raingauge at the head of the torrent and a sediment trap (~14-day resolution) provide a detailed record which extends from October 2001 to April 2005. Comparison between the sediment flux and rainfall series demonstrates the importance of precipitation extremes in triggering coarse sediment delivery. Typically one major sediment evacuation event occurs each year producing a distinct episodic output of coarse sediment. These events have similar yields and occur with an apparent regularity. Grain-size analysis of trapped sediment suggests a supply and exhaustion signal, and the differential role of processes across the sediment–water flow spectrum.

Key words mountain torrent; rainfall extremes; sediment yield; UK

INTRODUCTION

Fluvial hazards in mountain areas are often associated with coarse sediment transport in mountain streams and torrent systems (Eisbacher & Clague, 1984; Davies, 1991; Hewitt, 2004). Understanding of these hazards is hampered by a lack of direct observations and where measurements have been made these are generally related to a few high magnitude events or have been averaged over longer periods of time (Ackroyd & Blakely, 1984; Haeberli *et al*., 1990; Martínez-Castroviejo *et al.*, 1991; Pelpola & Hickin, 2004). This results in incomplete or low resolution records from which the structure of sediment delivery cannot be adequately discerned. High resolution records are necessary in order to test hypotheses about sediment delivery from torrent systems, in particular whether the release of coarse sediment can be related to a particular hydrological trigger or sediment recharge rate (Jakob *et al*., 2005). More recently, several studies have begun to assemble high resolution and longer-term results which provide fresh insights into sediment dynamics in mountain torrents (Rickenmann, 1997; Marchi *et al*., 2002; Lenzi *et al.*, 2003, 2004), although it is still argued (Marchi *et al.*, 2002) that an understanding of the significance of controlling variables remains an important challenge. Similarly, with regard to suspended sediment transport, Nistor & Church (2005) demonstrate that the majority of sediment flux occurs in discrete, infrequent episodes that form brief periods within runoff events. There was no consistent correlation between runoff and sediment yield, and small events were supply limited.

This paper describes a unique, high resolution record of coarse sediment flux (sediment trap infilling) and rainfall data from a mountain torrent (Iron Crag) in the English Lake District. By comparing these data this study aims to: (a) demonstrate the importance of precipitation extremes in triggering coarse sediment delivery, and (b) test the hypothesis that the release of sediment occurs only after the channel bed has been recharged with sufficient debris (Bovis & Jakob, 1999).

STUDY CATCHMENT

The Iron Crag torrent (Long. 3°05′W, Lat. 54°42′N) is a gully-head stream system dissecting the north-face of a convex–concave hill (609 m a.m.s.l.) in the Lake District, northern England (Fig. 1). The convex hilltop portion of the catchment (area 12 550 m^2, mean gradient 0.16 m m^{-1}) is an acid grass and heather dominated moorland. Runoff from the hilltop catchment converges at the gully head at a sharp break of slope (~570 m a.m.s.l.) where it is directed into the steeper concave face of the hillslope. At this point the torrent consists of a series of unvegetated, interconnected hillslope sediment sources, a bedrock step-pool channel, and a basal debris fan (440–395 m a.m.s.l.). The coarse sediment flux data reported in this study relate to the steep upper portion of the torrent (~570 to 507 m a.m.s.l.). The zone above the channel sediment trap (mean gradient 0.50 m m^{-1}) is divided into 3129 m^2 of hillslope sediment sources (colluvium, and rockfaces) and 456 m^2 of channel bed. Previous investigations have shown that this zone has very high rates of hillslope sediment supply (Johnson & Warburton, 2002) and channel sediment flux (Johnson & Warburton, 2006). Further details of the study catchment are reported by Johnson & Warburton (2002, 2003, 2006).

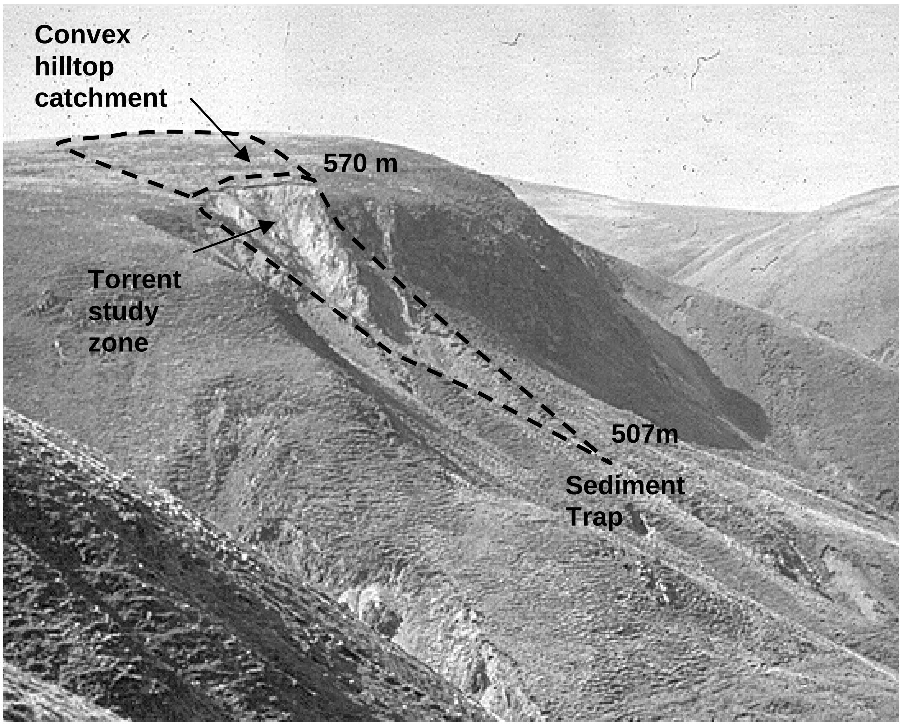

Fig. 1 Iron Crag study catchment above the sediment trap, with convex and concave hillslope components.

MONITORING AND MEASUREMENT PROGRAMME

The Iron Crag catchment has been instrumented since June 1998. Previous invest-tigations have sought to establish relationships between sediment transfer dynamics and hydro-meteorological conditions over a range of timescales (e.g. Johnson & Warburton, 2002, 2003, 2006; Warburton *et al.*, 2003). In this study we report results from the channel sediment trap (also a v-notch weir), and catchment raingauge. The sediment trap/weir was constructed in May 2000 with infrequent emptying of sediment throughout 2000. Further monitoring during much of 2001 (March–October) was prohibited by Foot and Mouth Disease land access restrictions. Therefore, data reported are those associated with the regular (~2 week) retrieval of deposited sediments from 19 October 2001 (baseline starting date) to 8 April 2005. Over this period of 1267 days (or 3.47 years) the interval between trap emptying events (n = 98) is not equal (3–41 days), but has a mode of 14 days. All reported sediment masses are standardized to dry mass values, using a combination of field and laboratory calibration data.

Grain size distributions of sediments recovered between 12 July 2002 and 1 April 2005 were determined in the laboratory using pebble plates (>16 mm) and sieves (63 µm–11.3 mm). Following Folk (1974) the grain size statistics are calculated logarithmically (in phi units) using graphical methods, here using GRADISTAT (Blott & Pye, 2001).

Rainfall has been monitored continuously since 3 September 1998, using a Rainew 100 tipping bucket raingauge® connected to a Hobo Event logger®. This is surround-ded by a 2.9-m radius turf-banked wall, at ~576 m a.m.s.l. All data are aligned to GMT calendar days. Catchment areas are obtained from total station survey data analysed in SURFER®.

RESULTS

Figure 2 shows the relationship between 15-min rainfall intensities (mm) and the sediment yield (kg dry mass) deposited in the channel sediment trap. Rainfall intensities are typically 0.5–1 mm per 15 min with peaks rising over 10 mm. Many of these higher intensity rainfall events occur in summer months, and tend to correlate to periods when sediment yields are elevated. However several points should be noted:

(a) The resolution of the two data series is very different. The rainfall series is a continuous record of 15 min intensity, whilst the sediment yields are obtained over an average period of 2 weeks. However, it is known from direct observation and previous studies (Johnson & Warburton, 2003) that large sediment yields tend to be related to discrete higher magnitude rainfall events (i.e. convective storms of short-duration, high intensity) and between these times sediment transport in the system is relatively inactive.

(b) The correlation between large sediment yields and rainfall events is variable. For example sediments emptied on 8 August 2003 closely relate to a single peak in rainfall on 30 July 2003 (7.62 mm per 15 min). There is similar correspondence with sediment yield on 1 August 2002 (rainfall 30 July 2002, 10.41 mm per 15 min), and 3 September 2004 (rainfall 29 August 2004, 4.83 mm per 15 min). In contrast, sediments emptied on 1 February 2002 (rainfall same date), relate to long-duration, lower intensity conditions (Johnson & Warburton, 2003).

(c) Sediment yields appear to be dominated by two populations: generally low yields up to approximately 0.5 t; and very large yields up to 5 t. Some of the largest yields should also be regarded as a minimum estimate as overfilling of the sediment trap was observed during the February 2002 event, and incision of the top surface of trapped sediments was noted on other occasions.

These characteristics imply a simple model for sediment yield from the torrent system. Sediment accumulates in the torrent bed until an event of sufficient intensity-duration combination triggers an almost catastrophic release of material resulting in a flushing of the stored sediment downstream. Such events typically scour the channel bed all the way to bedrock in the source areas of the torrent system.

Figure 3 shows a distinct stepped profile in the cumulative sediment yield from the torrent system over time. These step changes in sediment yield are spaced at approximately one major event per year. It is tempting to conclude that this reflects a characteristic sediment supply rate and time frame (~one year) for the system to recharge the channel bed with sediment before the next failure. However, Fig. 2 shows that the rainfall triggering events that can produce large sediment yields are relatively few in the record (e.g. there are only 11, 15-min intensities which exceed 4 mm). Therefore the periodicity of large yields is probably indicative of the combined influence of meteorological triggers (transport-limited), and sediment availability (supply-limited). This corroborates previous observations of channel sediment transfer at this site (Johnson & Warburton, 2006).

Figure 4 shows the relationship of rainfall characteristics (maximum and mean intensity, mm h^{-1}) and sediment yield between trap emptying events (kg dry mass). Both plots show a positive relationship between rainfall magnitude and yield. However

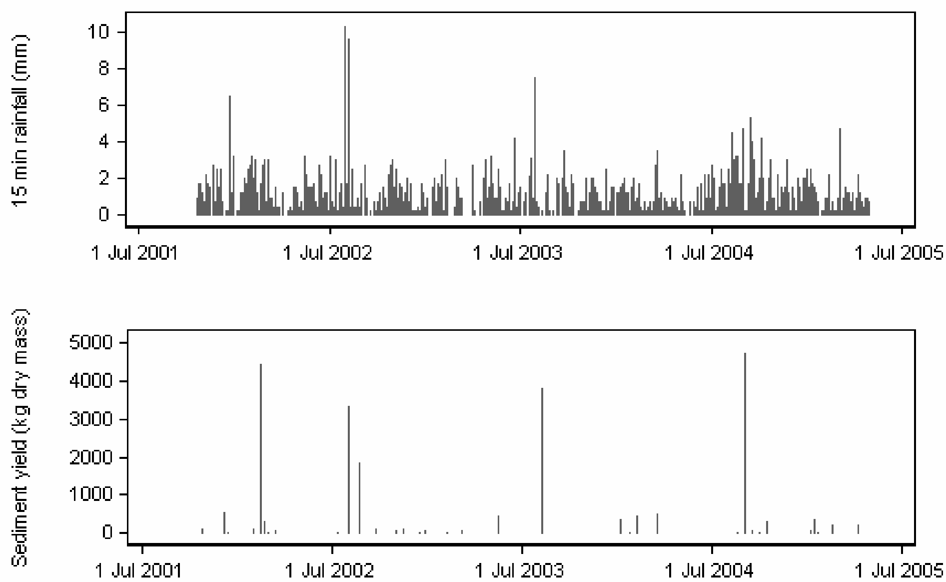

Fig. 2 Coarse sediment yield and 15-minute rainfall intensities between October 2001 and April 2005 at Iron Crag.

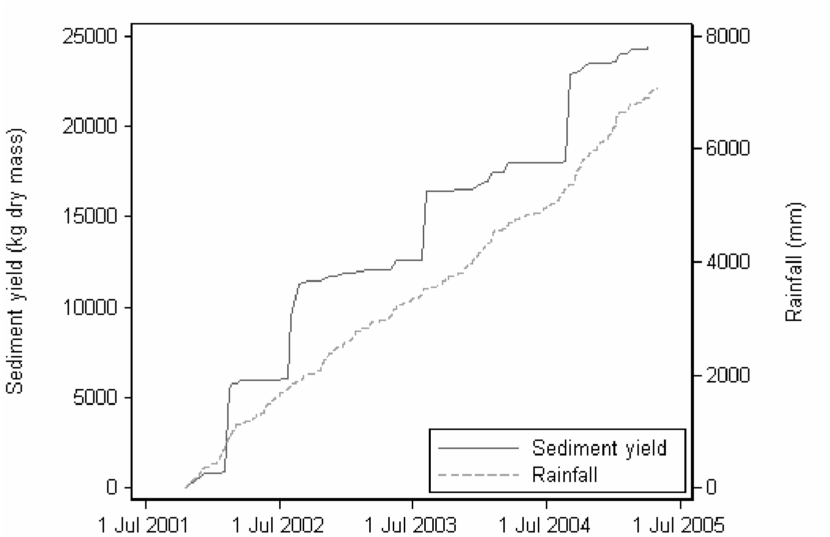

Fig. 3 Cumulative sediment yield (kg dry mass) and rainfall (mm) between October 2001 and April 2005 at Iron Crag.

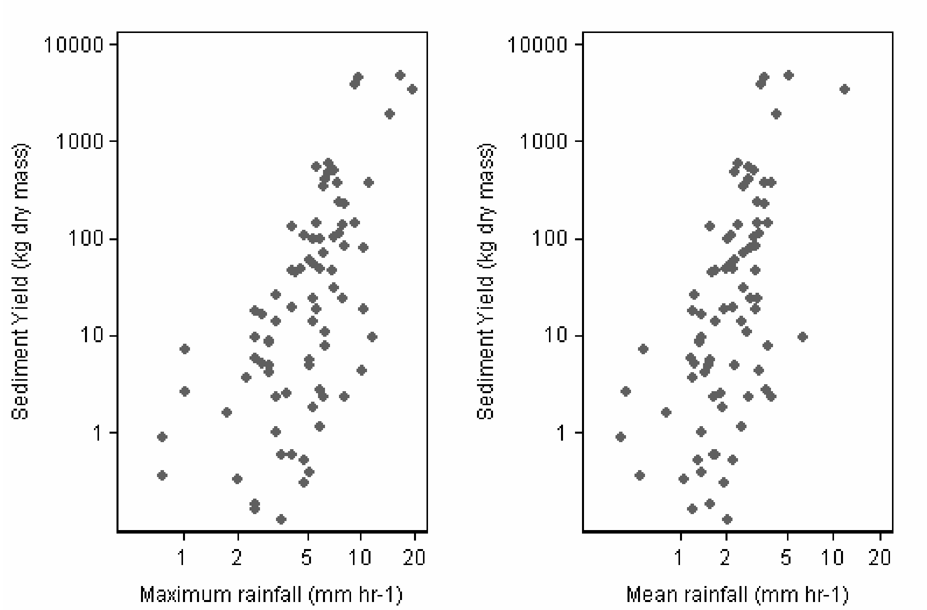

Fig. 4 Relationship between sediment yield (kg dry mass) and hourly rainfall intensity (maximum and mean) between trap emptying events at Iron Crag.

these relationships are relatively weak; R^2 values are 0.35 and 0.38 for mean and maximum rainfall respectively. The reasons for this are as follows:

(a) Following the depletion of channel sediments by a large event, subsequent yields during recharge will be supply-limited. This increases the range in possible yield below the upper transport-limited boundary. Figure 4 clearly show such a characteristic spread in the data, similar to that reported by Hegg & Rickenmann, (1999) for the Erlenbach torrent, Switzerland.

(b) The 14-day average resolution in the sediment yield series means rainfall characteristics are generalized for the periods between trap emptying. Thus the exact triggering values cannot always be clearly assigned to particular yield events. What is more, multiple small events during the period between emptying cannot always be recognized in the deposited sediments. However, direct observation shows that most of the larger sediment yield events involve en-masse transport in relation to an intense rainfall peak and these are usually easily identified in the record.

(c) Although there is a direct relationship between rainfall and runoff, channel discharge has not been monitored for all events. Inevitably there will be some differences in the nature of this relationship particularly in different seasons when antecedent conditions vary, e.g. snowmelt in winter. Analysing why these relationships show so much scatter is important in suggesting processes operating in the torrent system, but is also a limitation with the current monitoring programme.

The episodic nature of sediment transport within the system (Fig. 3) means the torrent will need to recover from such major disturbance over an extended range of hydrological events. One way of assessing this is to look at the variation of mean grain-size in the trapped sediments (Fig. 5). If we examine this variability with respect to the time elapsed since the occurrence of three major sediment transport episodes (trap emptying dates): 1 August 2002, 8 August 2003, 3 September 2004, a general pattern emerges. Figure 5 highlights this using a smoothing line (lowest) which is the locally weighted regression of *y* on *x* for the individual data sets. Mean grain-size is markedly larger during sediment flushing events and in the immediate aftermath, but through time decreases as the torrent system recovers from disturbance. Typically mean grain-size during all but the largest events averages approximately 2.5 mm. The observed variability is likely to reflect local sediment supply and exhaustion effects acting within the channel bed, complicated by the range of sediment-water flows that take place in the channel. Fifty to 100 days after a major flushing event the grain-size appears to return to normal values. It is uncertain whether the coarsening trend thereafter is significant or not.

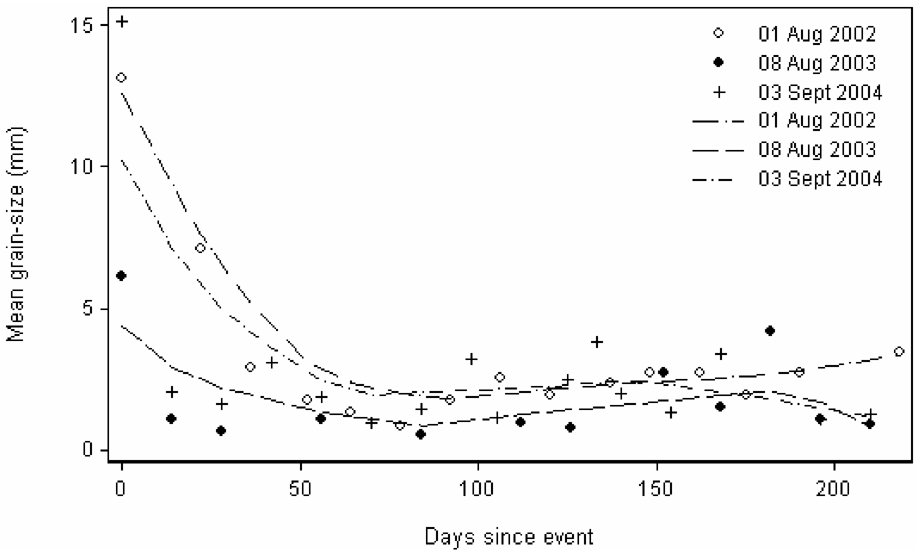

Fig. 5 Variation in mean grain-size (mm) of trapped sediments following large yield events: 1 August 2002; 8 August 2003; and 3 September 2004.

DISCUSSION

The importance of rainfall intensity-duration in triggering sediment transfer in the Iron Crag torrent system is clearly shown in this paper. However the significance of sediment recharge (supply control) is indirectly inferred. Figure 3 suggests an interval of approximately six months (1 February 2002–1 August 2002) to a year (1 August 2002–8 August 2003; 8 August 2003–3 September 2004) between successive major transport episodes. Furthermore, Fig. 5 has demonstrated a recovery to normal mean grain-size over a shorter period (50–100 days) than that suggested in Fig. 3. Johnson & Warburton (2002) demonstrate that the supply of hillslope sediments to the channel is seasonally variable, with elevated activity in winter and spring months, in association with freeze-thaw activity. Hence it can be hypothesized that it is not only the absolute length of time since the last major event that conditions recharge, but also the time of year. Intervening hydrological events will re-organize juvenile areas of sediment deposition. To develop this knowledge temporally and spatially specific data of sediment supply, storage and yield are required. The authors have obtained such data for the study zone at Iron Crag, using a sediment budget methodology. Analysis of this second budget (April 2002–April 2003) of sediment dynamics of the Iron Crag system is forthcoming.

Further understanding will result from a spatially and temporally distributed sediment budget of the torrent; a comparison of sediment yield directly to runoff rather than using rainfall as a surrogate (e.g. Rickenmann, 1997; Nistor & Church, 2005); knowledge of intra-event sediment-water flow processes (e.g. Arattano & Franzi, 2004); and measurement of both sediment yield and hydrological events at similar resolutions (e.g. Rickenmann, 1997; Lenzi *et al.*, 1999).

CONCLUSIONS

The results from this study clearly support previous assessments of the Iron Crag system (Johnson & Warburton, 2002, 2003, 2006) which suggest coarse sediment flux from the torrent is highly episodic and related to meteorological triggers. The following general conclusions can be stated:

(a) Extreme precipitation events are the main triggering mechanism promoting coarse sediment instability in the torrent system. Although there is a weak correlation between both maximum and mean rainfall intensity, and event magnitude, there is considerable variation in the relationship. Thus, no simple threshold for predicting sediment transport during large events is identified.

(b) Coarse sediment delivery from the torrent system is highly episodic with a single major sediment transport event occurring each year, often following a major summer rainstorm. These events have similar sediment yields and occur with an apparent regularity.

(c) Grain-size analysis of trapped sediment following large events suggests a supply and exhaustion signal, conditioned by different sediment-water flows acting in the torrent channel.

REFERENCES

Ackroyd, P. & Blakely, R. J. (1984) En masse debris transport in a mountain stream. *Earth Surf. Processes Landf.* **9**, 307–320.

Arattano, M. & Franzi, L. (2004) Analysis of different water-sediment flow processes in a mountain torrent. *Nat. Haz. Earth Sys. Sci.* **4**, 783–791.

Blott, S. J. & Pye, K. (2001) Gradistat: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surf. Processes Landf.* **26**, 1237–1248.

Bovis, M. & Jakob, M. (1999) The role of debris supply conditions in predicting debris flow activity. *Earth Surf. Processes Landf.* **24**, 1039–1054.

Davies, T. R. H. (1991) Research of fluvial processes in mountains: a change in emphasis. In: *Fluvial Hydraulics of Mountain Regions* (ed. by A. Armanini & G. DiSilvio), 251–266. Springer-Verlag, Berlin, Germany.

Eisbacher, G. H. & Clague, J. J. (1984) Destructive mass movements in high mountains: hazard and management. *Geological Survey of Canada Paper 84-16*.

Folk, R. L. (1974) *Petrology of sedimentary rocks*. Hemphill Publishing Company, Austin, USA.

Hegg, C. & Rickenmann, D. (1999) Comparison of bed load transport in a steep mountain torrent with a bed load transport formula. IAHR Congress, Graz, Austria, August 1999.

Hewitt, K. (2004) Geomorphic hazards in mountain environments. In: *Mountain Geomorphology* (ed. by P. N. Owens & O. Slaymaker), 187–218. Arnold, London, UK.

Haeberli, W., Rickenmann, D., Zimmermann, M. & Rösli, U. (1990) Investigation of 1987 debris flows in the Swiss Alps: general concept and geophysical soundings. In: *Hydrology in Mountainous Regions. II Artificial Reservoirs; Water and Slopes*, 303–310. IAHS Publ. 194. IAHS Press, Wallingford, UK.

Jakob, M., Bovis, M. & Oden, M. (2005) The significance of channel recharge rates for estimating debris-flow magnitude and frequency. *Earth Surf. Processes Landf.* **30**, 755–766.

Johnson, R. M. & Warburton, J. (2002) Annual sediment budget of a UK mountain torrent. *Geogr. Ann.* **84A**(2), 73–88.

Johnson, R. M. & Warburton J. (2003) Regional assessment of contemporary debris-flow activity in Lake District mountain catchments, northern England: occurrence, scale and process. In: *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment* (ed. by D. Rickenmann & C. -L. Chen), 965–976. Millpress, Rotterdam, The Netherlands.

Johnson, R. M. & Warburton, J. (2006) Variability in sediment supply, transfer and deposition in an upland torrent system: Iron Crag, northern England. *Earth Surf. Processes Landf.* (in press).

Lenzi, M. A., D'Agostino, V. & Billi, P. (1999) Bed load transport in the instrumented catchment of the Rio Cordon. Part I: Analysis of bed load records, conditions and threshold bed load entrainment. *Catena* **36**, 171–190.

Lenzi, M. A., Mao, L. & Comiti, F. (2003) Interannual variation of suspended sediment load and sediment yield in an alpine catchment. *Hydrol. Sci. J.* **48**(6), 899–915.

Lenzi, M. A., Mao, L. & Comiti, F. (2004) Magnitude–frequency analysis of bed load data in an Alpine boulder bed stream. *Water Resour. Res.* **40**(7) doi: 10.1029/2003WR002961.

Marchi, L., Arattano, M. & Deganutti, A. M. (2002) Ten years of debris-flow monitoring in the Moscardo Torrent (Italian Alps). *Geomorphology* **46**, 1–17.

Martínez-Castroviejo, R., García-Ruiz, J. M., Díez, J. C. & Alvera, B. (1991) Coarse sediment transport in an experimental high mountain catchment of Central Pyrenees, Spain. *Z. Geomorphol. Suppl. Bd* **83**, 105–114.

Nistor, C. J. & Church, M. (2005) Suspended sediment transport regime in a debris-flow gully on Vancouver Island, British Columbia. *Hydrol. Processes* **19**, 861–885.

Pelpola, C. P. & Hickin, E. J. (2004) Long-term bed load transport rate based on aerial-photo and ground penetrating radar surveys of fan-delta growth, Coast Mountains, British Columbia. *Geomorphology* **57**, 169–181.

Rickenmann, D. (1997) Sediment transport in Swiss torrents. *Earth Surf. Processes Landf.* **22**, 937–951.

Rickenmann, D., D'Agostino, V., Dalla Fontana, G., Lenzi, M. & Marchi, L. (1998) New results from sediment transport measurements in two Alpine torrents. In: *Hydrology, Water Resources and Ecology in Headwaters* (ed. by K. Kovar, U. Tappeiner, N. E. Peters & R. G. Craig) (Proc. HeadWater'98, Meran/Merano, Italy, April 1998), 283–289. IAHS Publ. 248. IAHS Press, Wallingford, UK.

Warburton, J., Evans, M. G. & Johnson, R. M. (2003) Discussion on "The extent of soil erosion in upland England and Wales". *Earth Surf. Processes Landf.* **28**, 219–223.