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EVIDENCE OF NON-CONTIGUOUS FLOOD DRIVEN COARSE SEDIMENT TRANSFER AND IMPLICATIONS FOR SEDIMENT MANAGEMENT

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ABSTRACT

We investigate gravel redistribution and morphological response of three headwater streams following the Storm Desmond floods of December 2015. Reactive management of the watercourses following the flooding concentrated on removal of gravel and clearing of vegetation, perceived as having been significant causes of local flooding. Aerial LIDAR and ortho-photography were employed to critically assess the location, type and magnitude of sediment mobilization, using an sUAV to capture imagery of lake sediment fans across the area. Whilst gravel was mobilized during the flood the volumes involved do not appear to be as high as anticipated, with little detectable change in lake fan deposits in the sink zone of the three study streams. Re-exposure of relict gravels on floodplains through stripping of surface vegetation and soils, gave the false impression of fresh deposition. Reactivation of wandering channel zones appear to have acted as buffers to large-scale sediment movement rather than acting as supply zones. Sediment accumulation through towns and villages was harder to quantify due to the rapid clean-up operation, however, the authors suggest that this may not be as large as assumed and the widespread dredging is likely to have caused more problems than it has solved as the bed of many watercourses is now highly susceptible to mobilisation following mechanical disruption of the previously strongly armoured surface.

Keywords: gravel-bed river, sediment transfer, DEM, extreme event, flood

1 INTRODUCTION

Heavy rainfall events in upland catchments in the UK can have spectacular impacts upon river channel morphology, and there is evidence to suggest it is the more extreme events that are the effective geomorphic agents in such settings (Milan, 2012). Carling (1986) reported complete evacuation of channel deposits in the headwaters of the Langdon and West Grain catchments in the north Pennines, with severe bedrock erosion, plucking of boulders from jointed limestone. Further downstream on the West Grain catchment an estimated 10 000 tonnes of gravel was deposited, with the formation of gravel berms, bars and boulder jams. Such events are often accompanied by slope failures including peat slides (Carling, 1986; Warburton et al., 2004; Johnson and Warburton, 2008), that often may supply sediment to slope-channel coupling zones (Harvey, 2001). As a result of delivery of large quantities of sediment to coupling zones, Harvey (2007) observed channel metamorphosis from single-thread to multi-thread in reaches of the Bowderdale and Langdale Becks, in the Howgill Fells, Cumbria. Other examples (Milan, 2012; Milan and Schwendel, 2019), identify little coupling between slope and channel zones, with gravel largely re-distributed within the channel-floodplain system.

Large quantities of sediment were mobilized in several Lake district streams during the Storm Desmond Floods of December 2015, and flooding was experienced in a number of areas including Glenridding, with evidence of sediment and large woody debris accumulation at “pinch-point” zones such as bridges. The assumption made was that there had been fresh gravel delivered to the channel from slope-channel coupling zones upstream, and consequently the channel management strategy following the event was to remove large quantities of gravel from the channel to reduce flood risk, with for example 20 000 tonnes of gravel reported to have been removed from Gledridding Beck (McCall, 2016). Such gravel removal was undertaken with no prior geomorphic assessment of the potential impacts, despite well-established knowledge of the potential destabilising effect of gravel extraction within river systems (e.g. Kondolf, 1994). This paper examines coarse sediment flux along three upland watercourses in the English Lake District in response following the Storm Desmond floods.

2 STUDY SITE

Heavy rainfall 4-6th December 2015, led to widespread flooding in Cumbria and across other parts of northern Britain. The flooding resulted from some exceptionally high rainfall totals across the Cumbrian fells, exceeding 300mm and breaking existing UK rainfall records. Three watercourses were examined for morphological change representing the principal upland alluvial channel types in the UK (Table 1). Moderate

Table 1. Channel characteristics of UK study watercourses.

Channel type	**River**	**Location (OS grid reference)**	**Elevation (m a.s.l.)**
Wandering	Church Beck flowing off the Coniston Fells	SD 29237 98260	160
Cascade/Step-pool	Church Beck flowing off the Coniston Fells	SD 28894 98486	170
Torrent	Liza Beck draining Brackenthwaite Fell	NY 16243 20981	170
Active sinuous single-thread	River Ellen draining Northern Lake District Fells	NY 15830 41321	39

gradient wandering reaches such as the one studied on Church Beck frequently occur along upland watercourses and are mostly associated with a downstream valley constriction trapping fluvio-glacial and lacustrine sediments upstream. Lower in the catchment shallow gradient active single-thread channels similar to the River Ellen study reach occupy wider valley bottom areas composed of finer sediment. In bedrock influenced areas, the typical channel form is steep gradient step-pool; well represented by the upper Church Beck study reach or torrent system seen on Liza Beck. Submerged alluvial fans on the River Derwent, Church Beck, Yewdale Beck and Newlands Beck were also investigated with a view to providing qualitative estimate of the gross volume and type of material mobilized.

3 METHODS

Erosion and deposition was quantified across the three sites through simple DEM subtraction (Milan *et al.*, 2011), using 2009 and post Storm Desmond LIDAR for the River Ellen; sourced from the Environment Agency (EA). A post Storm Desmond sUAV survey was undertaken to generate orthophoto and terrain data for the Church Beck and Liza Beck sites, retrieved using a “Dji Phantom 3 professional” georeferenced using RTK GPS. All sites were subjected to a fluvial audit (Sear *et al.* 1995), and photographic survey of the lake fans on Church Beck and several other similar watercourses in the area were collected using the same sUAV with multiple image stitching using structure from motion, generating an orthophoto for comparison with pre-event imagery available on Google Earth. Reported error on historic EA LIDAR (±0.15 m) was used with the error computed for the drone data (±0.08 m) to calculate a combined error for the change surfaces generated (±0.18 m). Changes within this error band were ignored when calculating volumes of erosion and deposition.

4 RESULTS

Figure 1 and Table 2 summarise the sediment volume change measures across the wandering channel

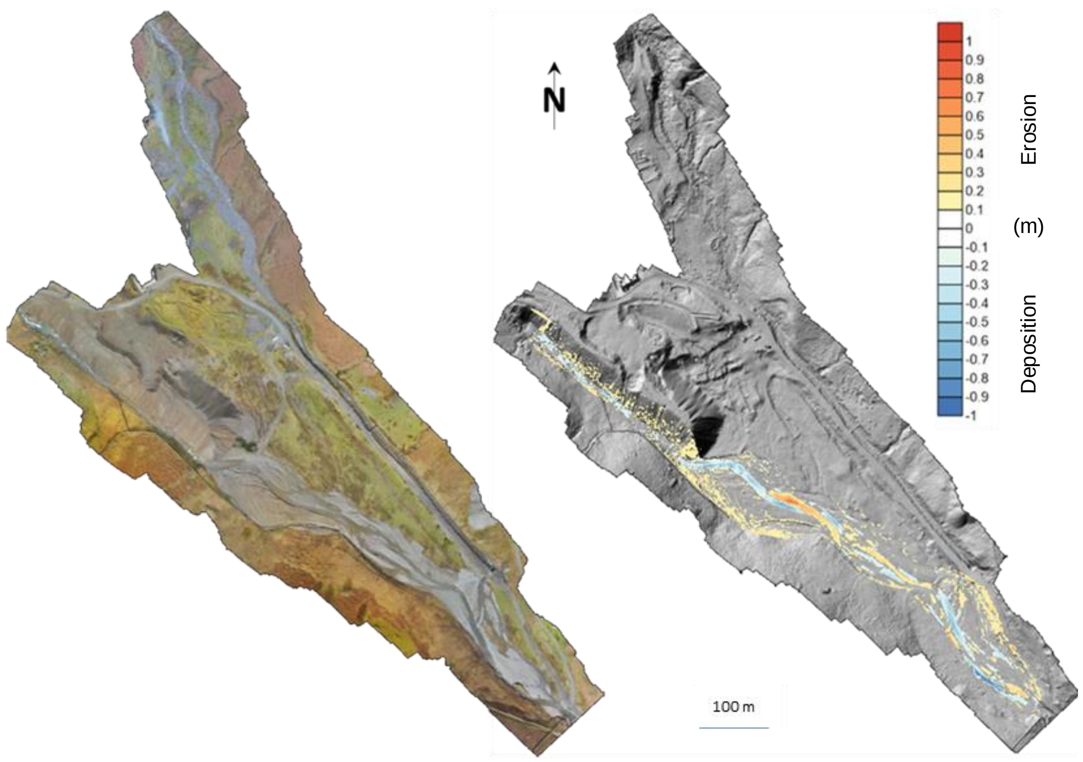

Figure 1. Orthophoto and DEM displaying measured morphologic change on the Church Beck wandering study site. The river flows south, Red Dell Beck enters from the left looking downstream.

reach on Church Beck following Storm Desmond. It is clear that change is limited essentially to channel switching across the wandering zone with the new low flow channel route reactivating palaeo-channel features linked to local deposition. The fan deposit created by Red Dell Beck entering from the left bank has also shown only minor change but clearly represents a zone of near permanent storage for coarse bedload with the feature dominated by large cobbles and small boulders (Figure 1). The overall loss of material from the wandering zone amounted to only 125 m^3, equivalent to less than 0.01 m of vertical change overall. It would thus appear that the reach probably acted to trap coarse sediment delivered from upstream whilst exporting comparatively small volumes of finer gravel bedload. This is attested to by the fluvial audit which found a propensity of mobile gravel lobes in the bedrock dominated reaches below the wandering zone.

Table 2. Sediment budget data for the three study sites.

River	**Volume deposited (m^3)**	**Volume eroded (m^3)**	**Volume balance (m^3)**	**Areal equivalent (m)**
Church Beck wandering reach	987.2	1703.8	-716.7	-0.050
Church Beck step-pool	30.8	302.9	-272.1	-0.186
Church Beck fan deposit	85.8	89.8	-4.0	-0.002
Liza Beck torrent	6404.3	5177.5	1226.8	0.036
River Ellen active single thread	7155.7	1807.4	5348.3	0.100

Figure 2 illustrates the erosion and depositional pattern recorded across the Liza Beck torrent study site. Here change appears to have been more significant and concentrated at a morphologic unit scale, with significant local stripping of the floodplain surface revealing coarser palaeo-gravels beneath. Surface roughness data (0.05 m resolution) suggests sediment fining in the downstream direction (Figure 3), suggesting size selective transport with larger boulders deposited in the upstream reaches whilst finer material is deposited across overbank zones up to 500 m downstream. Such processes in the long-term probably explain the formation of the multiple fan deposits seen across the wider valley. The sediment budget (Table 2) suggests an almost neutral change along the study reach with erosive losses almost matching depositional gains downstream. The fluvial audit suggests that only finer sediment stripped from overbank areas was exported from the study reach (Figure 4).

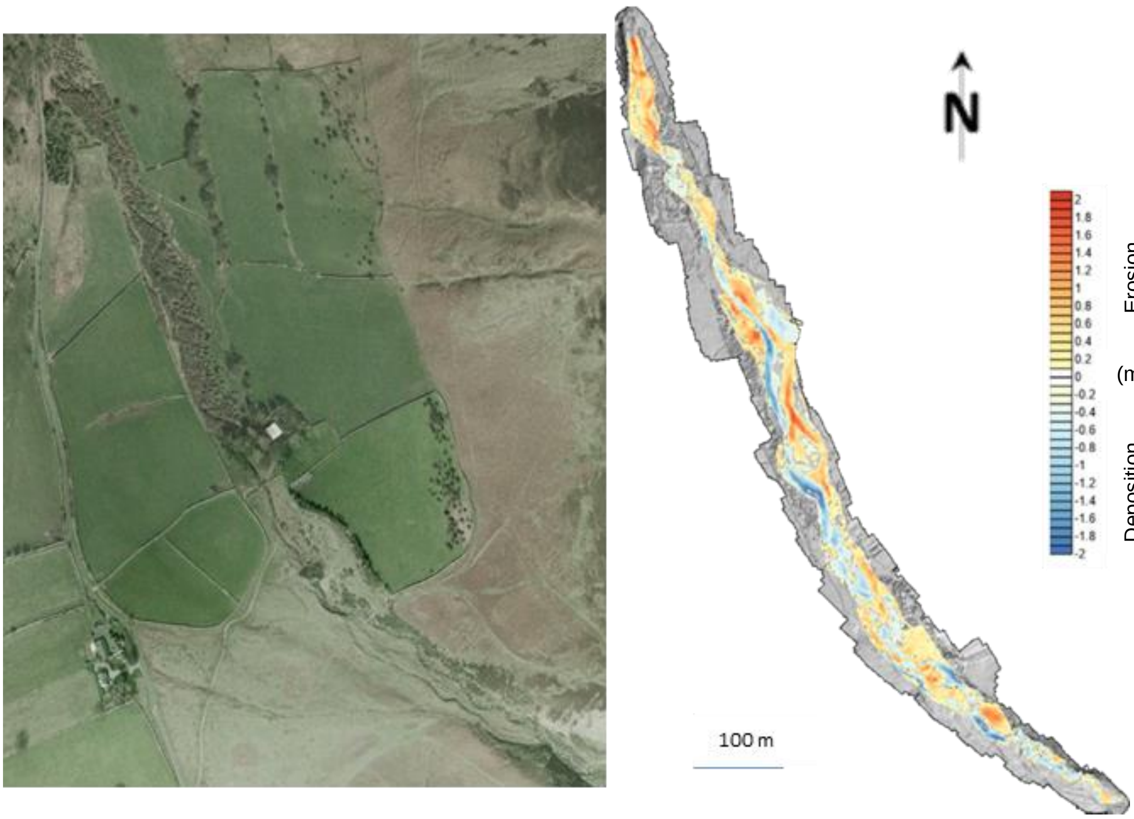

Figure 2. Orthophoto and DEM displaying measured morphologic change on the Liza Beck cascade/step-pool study site. Flow is to the south.

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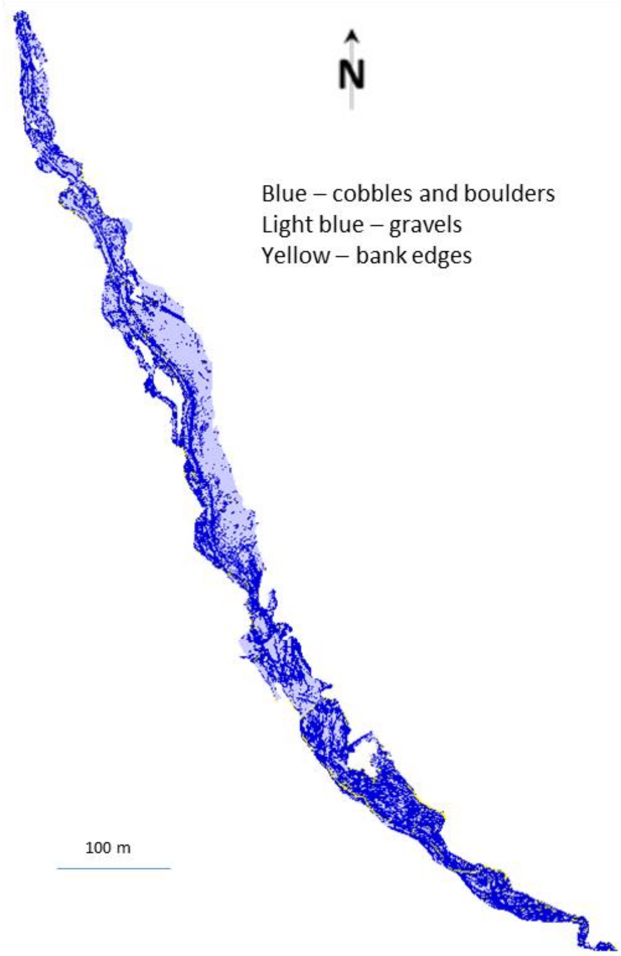

Figure 3. Surface roughness variation along the Liza Beck cascade/step-pool study site.

Figure 4. Evidence of overbank fine sediment stripping along Liza Beck.

Figure 5 and Table 2 suggest that the active sinuous single-thread reach of the River Ellen has accumulated sediment most notably in-channel with more patchy erosion and deposition across the floodplain. Evidence from the fluvial audit suggests localised bank erosion along outer bends and due to cattle poaching and deposition across the bed of the channel forming gravel riffle units and mixed sediment in-channel berms which have become vegetated. Accretion in the channel amounts to an average bed raising of 0.10 m which is likely to be significant from a flood risk perspective.

Overall sediment transport along Lakeland rivers was assessed visually, comparing Google Earth imagery of lake fan deposits on Church Beck entering Lake Coniston, the River Derwent entering Derwent Water and

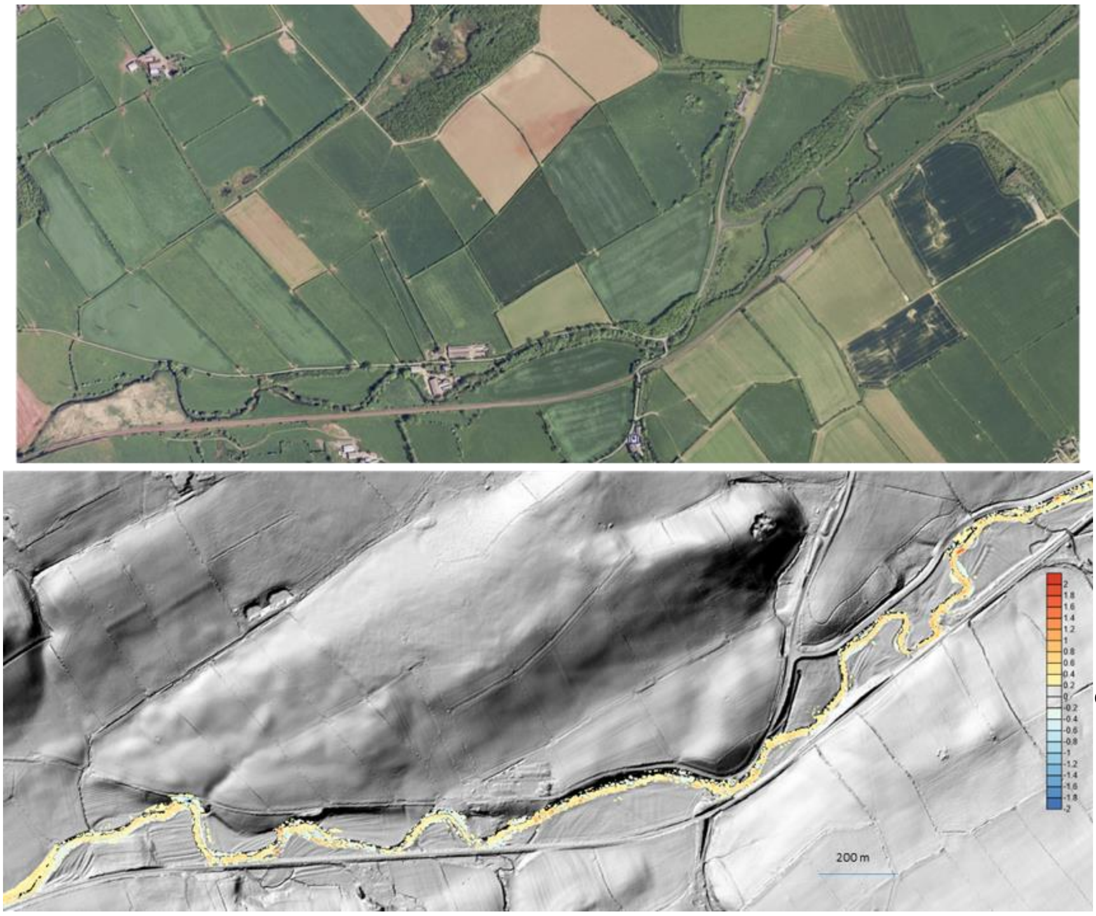

Figure 5. Orthophoto and DEM displaying measured morphologic change on the low gradient River Ellen active single thread study site. Flow direction is to the west.

Braithwaite Lake and Newlands Beck entering Braithwaite Lake (Figure 6). Despite differing water levels it is clear that there has been no significant growth of these features following Storm Desmond. This suggests that overall sediment movement along the watercourses assessed during Storm Desmond largely comprised redistribution of material within the channel-floodplain system, rather than sediment being evacuated out of the system.

5 DISCUSSION

It is known that the distribution of sediment stores and sinks reflects, and in turn influences, the routes and distances of sediment transport, providing a measure of the (dis)connectivity of any given landscape (Brunsden and Thornes, 1979; Meade, 1982; Wohl et al., 2019). This has been clearly demonstrated at the channel type scale on Church Beck and the morphologic unit scale on Liza Beck. This discontinuity in sediment transfer has been described as a 'jerky conveyor belt' (Ferguson, 1981) and different morphologic units are characterised by different storage times, with shorter storage periods for bars, and greater storage periods for floodplains (Meade, 1982). It is suggested here that the coarsest sediment on all of the study rivers is effectively in near permanent storage on the upland watercourses studied here with the current flood regime incompetent to transport such sediment any great distance. Change, whilst appearing dramatic is largely confined to stripping of finer sediments to expose coarse lag deposits and to a more general movement along the system of bedload gravels.

Figure 6. Lake fan change following Storm Desmond.

Transport also appears to be restricted to gravels and small cobbles over a more stable coarser surface composed of lag deposits. Where lag sediment is re-exposed by flood erosion of overlying fines this acts to moderate further sediment loss downstream, however the exposure of large areas of coarse material gives the impression of new sediment delivery. Phase I transport (*sensu* Jackson and Beschta, 1987) appears to dominate transport processes especially in upland reaches.

The degree of sensitivity to change governs the robustness of a feature and longevity of storage zones dictates how the effects of geomorphic changes are propagated through a catchment (Harvey, 2002). The watercourses studied here appeared display a high degree of disconnectivity, with storage of gravel rather than transfer dominating. Such behaviour effectively suppresses the propagation of geomorphic change through the catchment (Thomas, 2001). Sediment transfer appears to be 'Blocked' (*sensu* Harvey, 2012), suppressing the supply of material to lower reaches.

6 CONCLUSIONS

The results of this study are conceptualised in Figure 7 and show that channel change is a function of sediment source zone activity with extensive scree slopes and mine spoil not presently contributing to the active gravel transport regime of the rivers audited. Connectivity with the active channel network has also been shown to be critical. The short-term fate of transported sediment may be transient with deposition as flood waters recede followed by re-entrainment and transport during the next geomorphologically effective event or it may be more permanent with sediment being locked up across accumulation zones where the current flow regime is incompetent to cause further downstream movement. It would appear that even under quite extreme floods bedload transport distances are small with most sediment recorded as moving between adjacent morphologic units similar to the behaviour reported by Milan *et al*. (2002). It is suggested that the relic coarse-sediment in the upland channels studied develop a long-term armour (Parker and Klingeman, 1982; Gomez, 1983) that is periodically exposed and locally reworked before being buried under fine deposits.

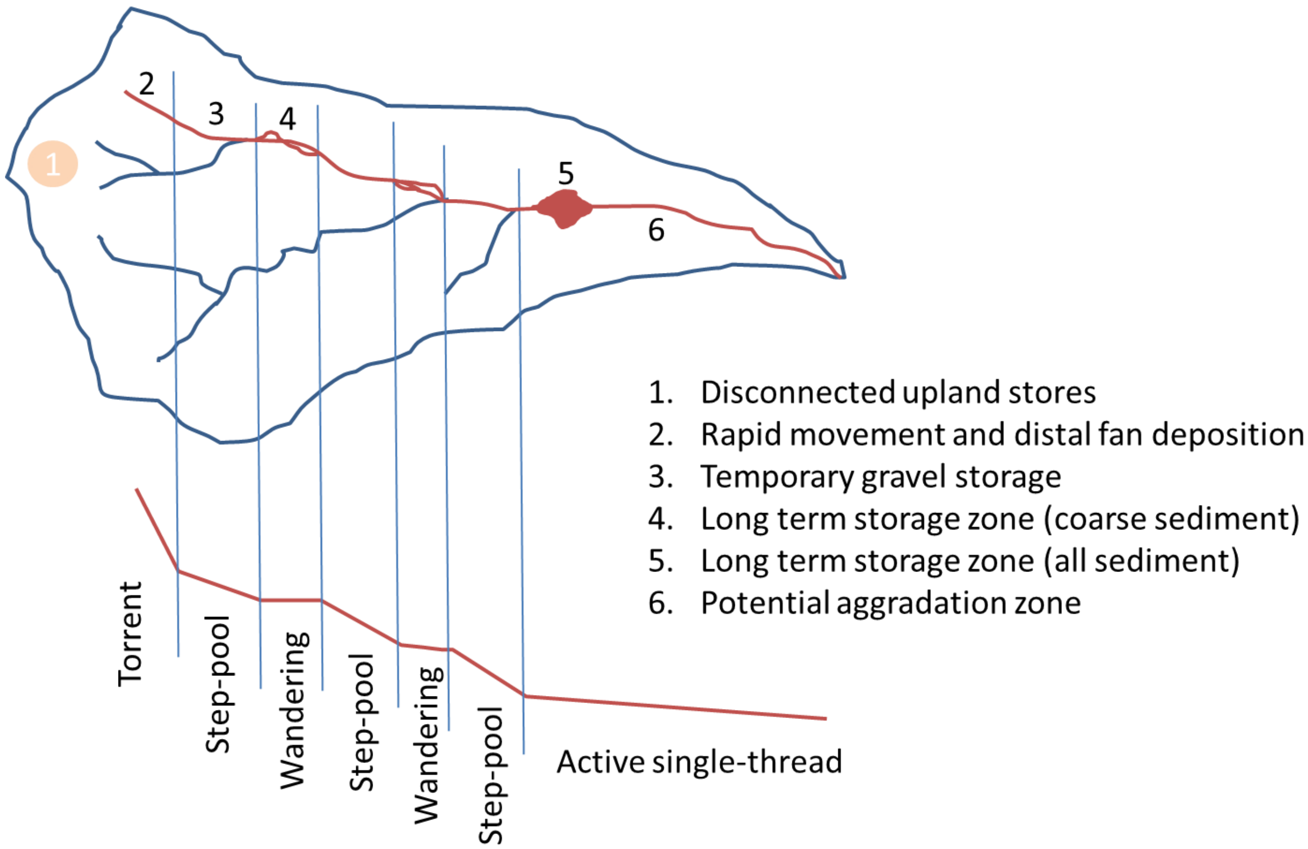

Figure 7. Summary bedload transport behaviour linked to channel type.

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