ASSESSMENT OF SHALLOW LANDSLIDE ACTIVITY FOLLOWING THE JANUARY 2005 STORM, NORTHERN CUMBRIA

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Introduction and background

Landslides are one of the most destructive geological processes and globally are a major cause of loss of life and economic damage. In North West England on 7-8 January 2005, an unprecedented number of shallow landslides occurred throughout the Northern Lake District Mountains following heavy rainfall which resulted in severe regional flooding with a loss of life. The impacts of these slope failures were widespread involving disruption and damage to roads, bridges and culverts; destruction of agricultural infrastructure; inundation of forestry plantations and farmland; loss of livestock; diversion of stream courses; and contamination of upland water courses with sediment.

This level of landslide activity has not been previously documented in the region and presents a rare opportunity to assess the controls on hillslope instability in an upland environment. Whilst an improved understanding of processes governing landslides does not directly translate into reduced risk, an understanding of physical process can provide significant steps towards effective risk reduction by identifying key trigger factors and site conditions susceptible to landslides.

A landslide involves displacement of rock, debris or earth down a slope under the influence of gravity and includes a wide range of rapid to slow mass movements. In terms of the present study the main type of landslide involves shallow translational debris slides where:

“mass displaces along a planar or undulating surface of rupture, sliding out over the original ground surface" (Cruden and Varnes, 1996) (Figure 1).

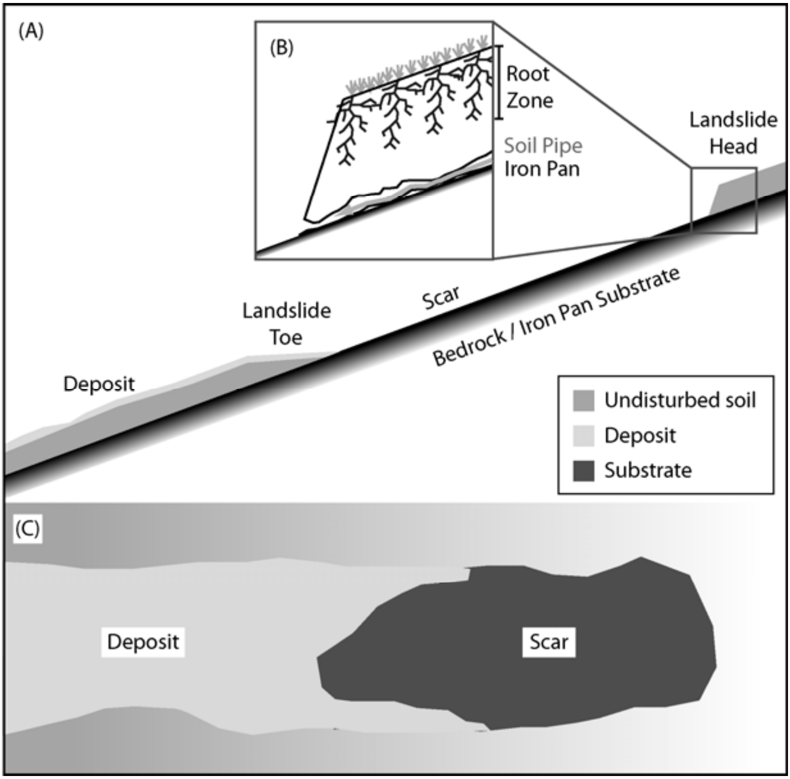


Figure 1. Schematic of a cross section through a shallow translational landslide (A) with inset showing typical soil profile (B) and planform of the scar area and deposit (runout zone) (C).

The slides can involve various combinations of bedrock and unconsolidated surficial material and are the most common form of landslide occurring in soils. Typically they have flat slide planes, which usually develop along a boundary between soil materials of different density or permeability (Figure 1). Depth to the landslide failure plane is usually in the range 1–3 m and the length of the slide is commonly large compared with its depth and greater than the landslide width. Following failure a distinctive scar remains on the hillside below which debris is deposited in a linear runout track (Figure 1).

Shallow landslide and debris flow features have been most extensively investigated in the Scottish Highlands (Innes, 1982, 1983, 1997, Ballantyne, 1986; Jenkins et al., 1988, Luckman, 1992) but also in parts of Wales (Statham, 1976; Addison, 1987; Winchester and Chaujar, 2002); the Lake District (Johnson and Warburton, 2003; Johnson et al., 2008); and the Howgill Fells of Northwest England (Wells and Harvey, 1987; Harvey, 2001). There is also a considerable body of detailed literature on peat mass movements (Warburton et al., 2004; Dykes and Kirk, 2006) that exhibit many similarities in form and process to slides occurring in shallow colluvial soils. These studies include inventories indicating magnitude and frequency, detailed morphological descriptions (Warburton et al., 2003) and studies on the hydrological (Warburton et al., 2004; Dykes and Warburton, 2007) controls on stability in peat.

Except for the studies listed above there have been very few detailed investigations of Lake District shallow landslides and slope failures. Several recent reports of notable events have appeared in the local media, for example BBC (2004) details the River Greta flood of 19 August 2004, which also coincided with substantial landslides at Lonscale Fell and also within the Vale of Threlkeld; and the Cumberland Geological Society Newsletter (Smith, 2005; Warburton et al., 2006; Smith, 2006), and the George Fisher Update (The Update, 2005) in respect of the January 2005 landslides. Other literature generally refers to much older deep-seated rock failures (Wilson, 2003). Notably there has been recent interest in large rock slope failures which are thought to have resulted from slope stress readjustments caused by the disruption of glacial / deglacial cycles (Brook and Tippett, 2002; Clark and Wilson, 2004; Wilson et al., 2004; Wilson, 2005; Wilson and Smith, 2006).

The aim of this paper is to describe the characteristics of the suite of shallow landslides which occurred in the 457 km^2 study area of the Northern Lake District in response to extreme rainfall between the 7th and 8th of January 2005 (Figure 2). Specifically our objectives are to:

1) Outline the distribution of shallow landslides with respect to local geology and topographic setting:
2) Describe the morphometric characteristics of the shallow landslides;

3) Produce an estimate of the total erosion from landsliding during the January 2005 storm event.

Based on this information we are able to present an overview of the geologic and geomorphological characteristics of the landslides and evaluate their importance in the overall Lakeland landscape.

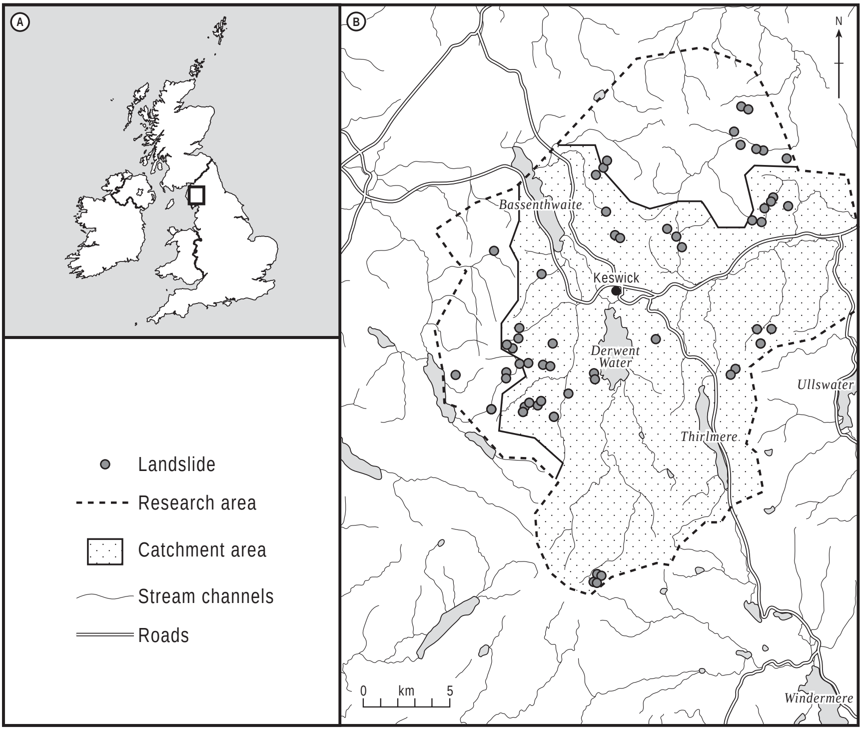


Figure 2. Research area location map. (A) Location of the research area and Bassenthwaite catchment in Northern England. (B) Detail showing Bassenthwaite catchment, location of significant landslides (January 2005).

Rainfall during the 2005 storm event

The landslides that occurred in the Lake District in January 2005 were predominantly triggered by elevated pore water pressures as a result of an intense rainfall event. Figure 3 displays a NIMROD RADAR image showing rainfall (mm) at 0200h and 2130h GMT on 7 January 2005. Intense rain is clearly visible over Cumbria in both time slice pictures .

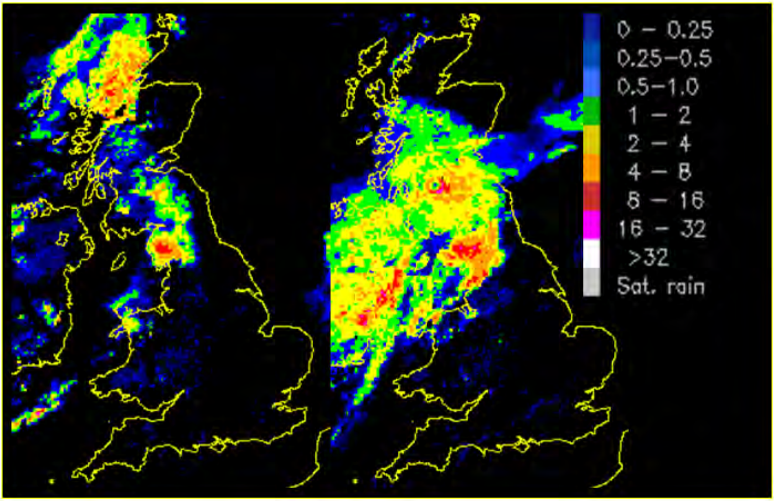


Figure 3. NIMROD RADAR image showing rainfall (mm) at 0200h (left) and 2130h (right) on 7 January 2005. Intense rain is clearly visible over Cumbria (© NERC-Met Office)

Heavy rainfall fell for most of the day, with a short easing of conditions between 0300h and 0900h GMT, resulting in many of the Environment Agency rain gauges in Central Lakeland recording some of the highest 24h values on record. Table 1 shows all the gauges that recorded in excess of 100 mm on 7 January 2005. All records are from automatic tipping bucket rain gauges (recording every 15 minutes) except those (*) that are from storage gauges (measured daily totals). Values are as high as 180 mm and span a broad area from the northwest fells, central Lakeland out to the eastern Lake District, which corresponds to the principal area of active landsliding (Figure 2). At some of the recording rain gauge sites hourly rainfall intensities exceeded 100 mm hr^{-1} for brief bursts. Rainfall of this exceptional type is a well documented trigger for shallow landsliding in upland environments (Dykes and Warburton, 2007, 2008) resulting in hillslope failures as shown in Figure 4.

The January 2005 shallow landslide inventory

The Lake District 2005 Landslide inventory is a complete record of 62 shallow translational landslides that occurred in the 457 km^2 research area (Figure 2). The research area corresponds broadly with the Bassenthwaite catchment (Figure 2) and was initially defined following reconnaissance in a light aircraft.

Table 1. Environment Agency rain gauge totals (> 100 mm) for 7th January 2005. All records are from automatic tipping bucket rain gauges (recording every 15 minutes) except those (*) which are from storage gauges (measured daily totals).

Rain Gauge	Daily Total (mm)
Rydal Hall	180 *
Honister Pass	164
Seathwaite Farm	159
Black Sail, Ennerdale	153
High Snab Farm, Newlands	148
Dale Head Hall, Thirlmere	144 *
Wet Sleddale Reservoir	137
St John's Beck	131
Grasmere, Tanner Croft	129 *
Burnbanks, Haweswater	126
Elterwater, Carr How	121 *
Moorahill Farm, Bampton	113
Brothers Water	112

Subsequently a small number of other failures, related to this event, have been identified outside this study area but are not included in the analysis. Landslides vary in size from small streamside scars, which are a few cubic meters in volume to major hillslope failures (Figures 4 and 6) as large as 1700 m^3. The Lake District January 2005 inventory is one of the largest contemporary shallow landslide inventories ever completed in the UK, its measurements and observations are consistent with older reports from similar Lake District landslides (Johnson, 2001; Johnson et al., 2008), and from other UK upland areas (Gifford, 1952; Beven et al., 1978; Newson, 1980; Innes, 1982, 1997; Jenkins, et al., 1988; Ballantyne, 2002).

An initial rapid aerial assessment of the full extent of the slope failures was undertaken at low level from a fixed-wing aircraft (11-22 April 2005). This provided immediate oblique aerial photographic evidence of the fresh failure features and was used to plan a programme of field-based assessments. Based on the preliminary air survey and using ground observations (from authors, and reported by a number of land managers) a detailed ground assessment of landslide sites was carried out.

Figure 4. Cockup landslide runout channel (NY 253 313, 350 masl). Field survey of landslide extent using differential GPS.

Field assessment of landslide sites involved differential GPS mapping and completion of a 'Slope Failure Reconnaissance Sheet' (SFRS), which describes the morphometry, morphological and material characteristics, drainage setting, post failure development and degree to which landslide debris was incorporated into local stream channel (slope-channel coupling) at each site.

Assessing shallow landslides in this way permits the construction of an inventory or database that can be analysed to assess the general features of the failures at the catchment scale. This includes the reconstruction of failure mechanisms and sediment budgets at each site.

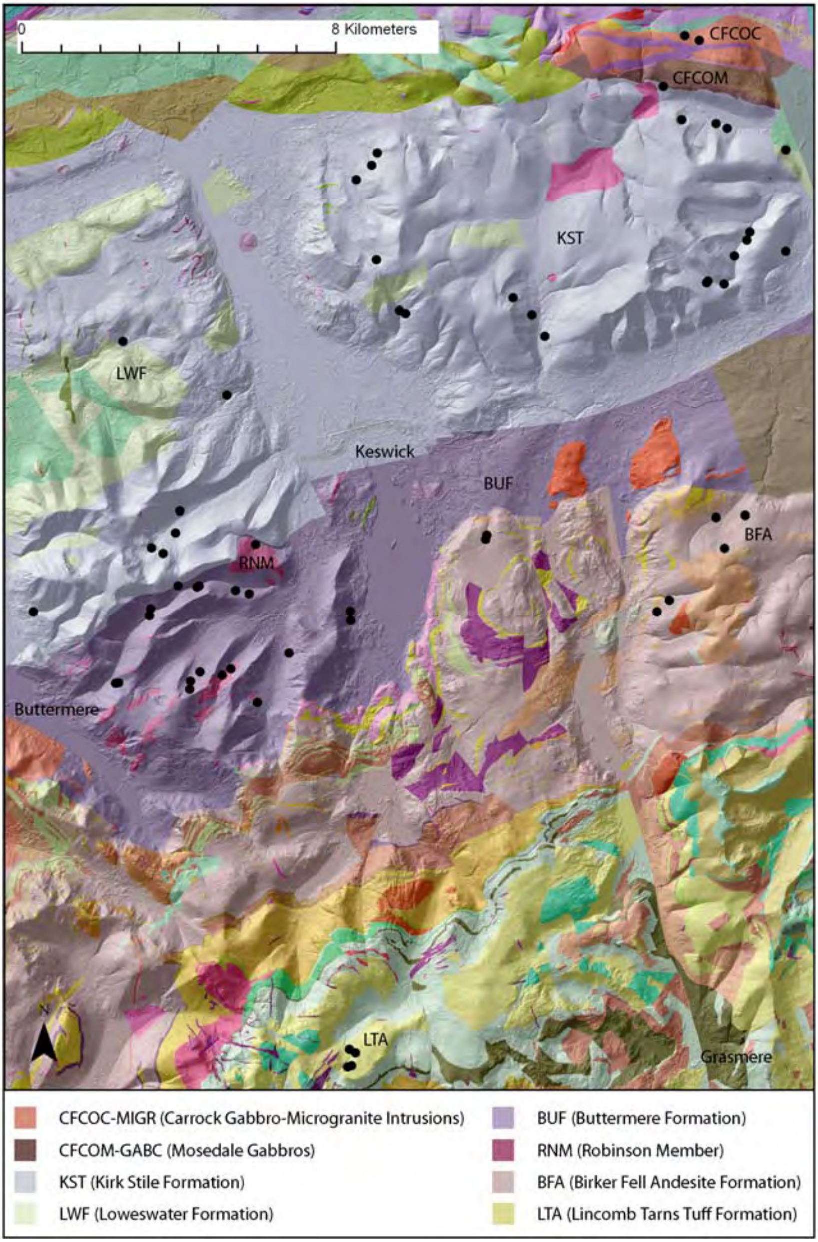
Landslide distribution

Figure 5 shows the distribution of landslide sites in relation to bedrock geology. The landslides are not evenly distributed across the 457 km^2 study area, but show a considerable degree of clustering (Figure 2 and 5). The majority of landslides occur to the North of the area on the Kirk Stile and Buttermere formations. Outside of these areas we see other clusters to the south (in the Angle Tarn area) and to the east of St John's Vale. Based on this evidence it is tempting to conclude that geology is exerting some control over the distribution. This must be treated cautiously because we are dealing with shallow landslides which occur in the overlying regolith and it is the characteristics of this material (soil properties, geotechnical strength, hydrological properties and vegetation) that are important in determining stability. Hence geology often exerts a secondary influence on failures through its influence on the general topographic form of the landscape and material properties. For example, the distribution of failures in Figure 5 will also reflect the particular storm rainfall distribution (and intensity) across the study area and the influence of the local topography. It is clear from the shaded relief shown in Figure 5 that most of the landslide sites occur on the steeper slopes.

Local controls

Analysis of local site factors reveals landslide source areas were widely distributed over a large altitudinal range between 200 and 700 m.a.s.l. (although predominantly 300-600 m.a.s.l.). Most failures occurred on slopes greater than 20° (but slopes as little as 10 degrees have been affected), and the depth of failure is shallow, rarely exceeding 1m in depth. The majority of failures (65%) involve sediment volumes of less than 100 m^3. Figure 6 is a good illustration of how local conditions can exert a significant influence on failure locations. This example documents a channel head debris slide at Poddy Gill, Mosedale (NY 327 332, 465 m.a.s.l.).

The diagram shows the vertical air photograph flown after the event (8 July 2005), and the reconstructed scour and deposition extent determined from air photograph analysis and differential GPS survey in the field (13 April 2005). Failure occurred at the channel head location and flowed downslope causing considerable new channel scour and depositing an extensive hillslope sediment trail and basal fan eventually running out into the River Caldew. At the head scar, scour depths in excess of 3.5 m were measured. The combination of the hollow-shaped local topography and channelised runoff probably account for failure at this location, by acting to alter local soil water conditions beyond a critical threshold value for slope stability (cf. Anderson and Burt, 1977; Pierson, 1977; Benda and Dunne, 1997). Although this is only evidence from a single site; conducting similar surveys across the full suite of shallow landslides which occurred in 2005 and combining these with knowledge from other landslide inventories in Britain (e.g. Dykes and Warburton, 2007, 2008) allows a general picture of failure settings to be constructed (Figure 7).



0
8 Kilometers
CFCOC
CFCOM
KST
LWF
Keswick
BUF
BFA
RNM
Buttermere
LTA
Grasmere
CFCOC-MIGR (Carrock Gabbro-Microgranite Intrusions)
CFCOM-GABC (Mosedale Gabbros)
KST (Kirk Stile Formation)
LWF (Loweswater Formation)
BUF (Buttermere Formation)
RNM (Robinson Member)
BFA (Birker Fell Andesite Formation)
LTA (Lincomb Tarns Tuff Formation)

Figure 5. Distribution of landslides in relation to solid geology (© NERC 2008).

Furthermore, observations of the failure scars after the event reveal several site characteristics that may have been important in defining the location or geometry of the failures. In particular, the presence of soil pipes at the head of the scars and the location of the failure plane at a hydrological discontinuity (Figure 1) corresponding with a hard layer which both impedes hydraulic conductivity and increases soil strength (Figure 1). For Lake District landslides, at over half the sites, this interface occurred at the soil-bedrock boundary (Figure 1). This is consistent with a range of other reports from landslide inventories both in the UK and elsewhere. For example, Gifford (1952) found on Exmoor that "Bare rock is now exposed at the head of most scars". However, this generalization should not be applied ubiquitously because soil depth does not always equate directly with the total thickness of unconsolidated material. In some locations, a translational failure plane may develop at any hydraulic conductivity discontinuity where positive pore water pressures can develop. Therefore the depth to the failure plane may be much less than the depth to competent bedrock. In regard to Lake District sites it was found:

1) At nearly two thirds of the sites the failure plane was in the overlying substrate and not at the bedrock interface as is assumed in many slope stability models;
2) Failure in the substrate occurred on more resistant layers often in association with an iron pan;
3) Soil pipes were found in the head scars of nearly three quarters of the landslides and these were located at or just above the failure plane.

<u>Classification of UK shallow landslides</u>

Figure 7 provides a classifcation of UK shallow landslides and is useful in the context of a landslide inventory because it provides a framework for comparing different inventories across upland environments. The basic structure of the typology describes the local topographic / hydrological setting ranging from streamside locations which are directly coupled to stream channel, through to open slopes which are largely uncoupled to drainage features. Landslide setting is important because it defines the link between the failure site and the extended hydrological network. Hillslope flush and open slope failures often have arrested runout tracks that are decoupled from the main drainage network whereas

streamside slope failures are directly coupled to the stream network often delivering all their sediment direct to the channel.

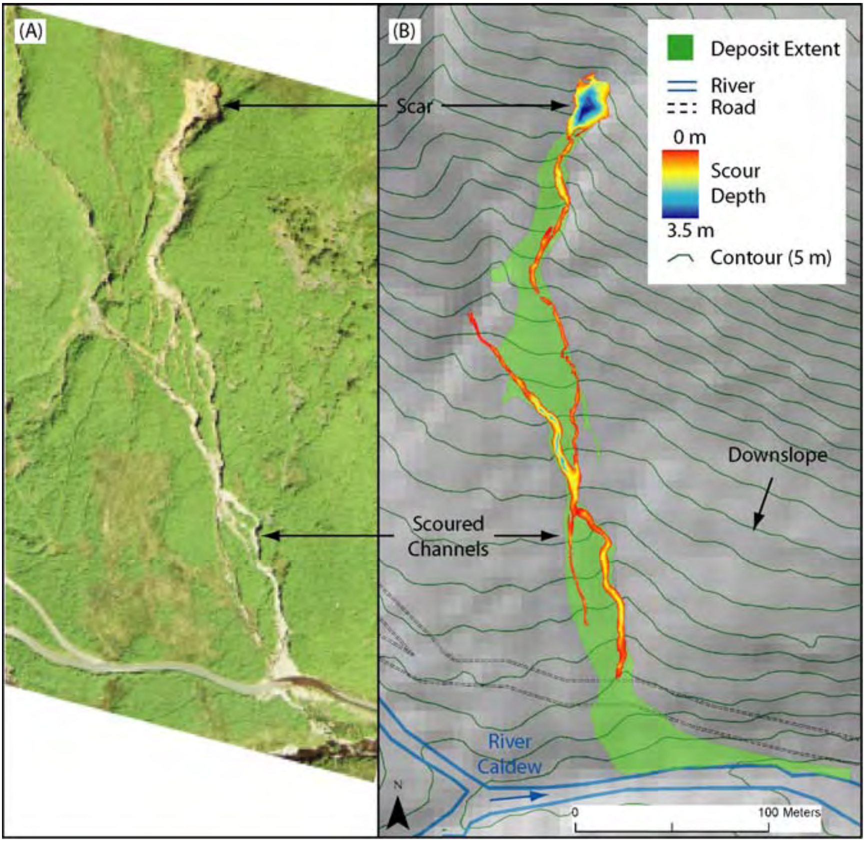


Figure 6. Typical example of a channel head debris slide, Poddy Gill, Mosedale (NY 327 332, 465 masl). The diagram shows the air photograph flown after the event and the reconstructed scour and deposition extent determines from air photograph analysis and differential GPS survey in the field.

These intimate links between the hydrological network and landslide source areas suggest sediment supply in these particular settings is potentially high. Similarly the material characteristics in each of these settings are described based on the dominance of mineral or organic (peaty) regolith. This is important because sediment type is a significant factor governing the mechanism and consequence of failure e.g. mineral soil versus blanket peat failures (Peaty debris slide often involve thin peat soils or organic rich mountain soils).

Combining a description of the local topographic setting, drainage and material characteristics often defines the conditions that are susceptible to failure. This simple typology has been applied to the January 2005 landslides and results are described below.

The morphology of shallow landslides (Figure 1 and Figure 7) needs to be carefully measured in order to define the geometry of the failures and to provide accurate estimates of the amount of material transfer. Figure 8 summarises the morphometry of the January 2005 landslides. The graph plots landslide width against landslide length with the distribution of each of these variables shown as histograms on the corresponding axes. The circles are proportional to the mean depth of each landslide measured in the scar area, these vary from 0.17 to 1.90 m. When comparing the geometric axes(length, width and depth) of observed landslide scars, width rarely exceeds length (i.e. aspect ratio is greater than or equal to one), hence many of the landslides have pronounced elongated failure scars. There is a clear bias in the data with the majority of landslides being less than 15 m in width and 40 m in length. There is also a tendency for the larger landslides to have the greater depths but there is considerable scatter in this relationship.

<u>Sediment yield from shallow landslides</u>

The relationship between width, length and depth of the landslide defines the failure volume. Failure volumes in this project were accurately surveyed in the field using differential GPS. of the failed sediment is required. However, in order to estimate the sediment yield in mass, a bulk density This was measured at each field site by collecting soil and sediment samples in the vicinity of the failure scar. Results of the sediment yield measurements are summarised in Figure 9, which shows a sediment budget (cumulative sediment yield (t)) for the January 2005 landslides. In this diagram landslides are grouped by landslide type (see Figure 7) and whether the landslide is coupled to a major stream channel, or not. It is clear from Figure 9 that over half of the landslides (36 out of 62) are coupled to stream channels and these contribute 6278 t of sediment to the drainage system (63 % of the total sediment produced from the landslides). Sediment sources cover the full range of hillslope failures for mineral soils, and involve additional failures of peaty debris from channel head and hillslope flush locations.

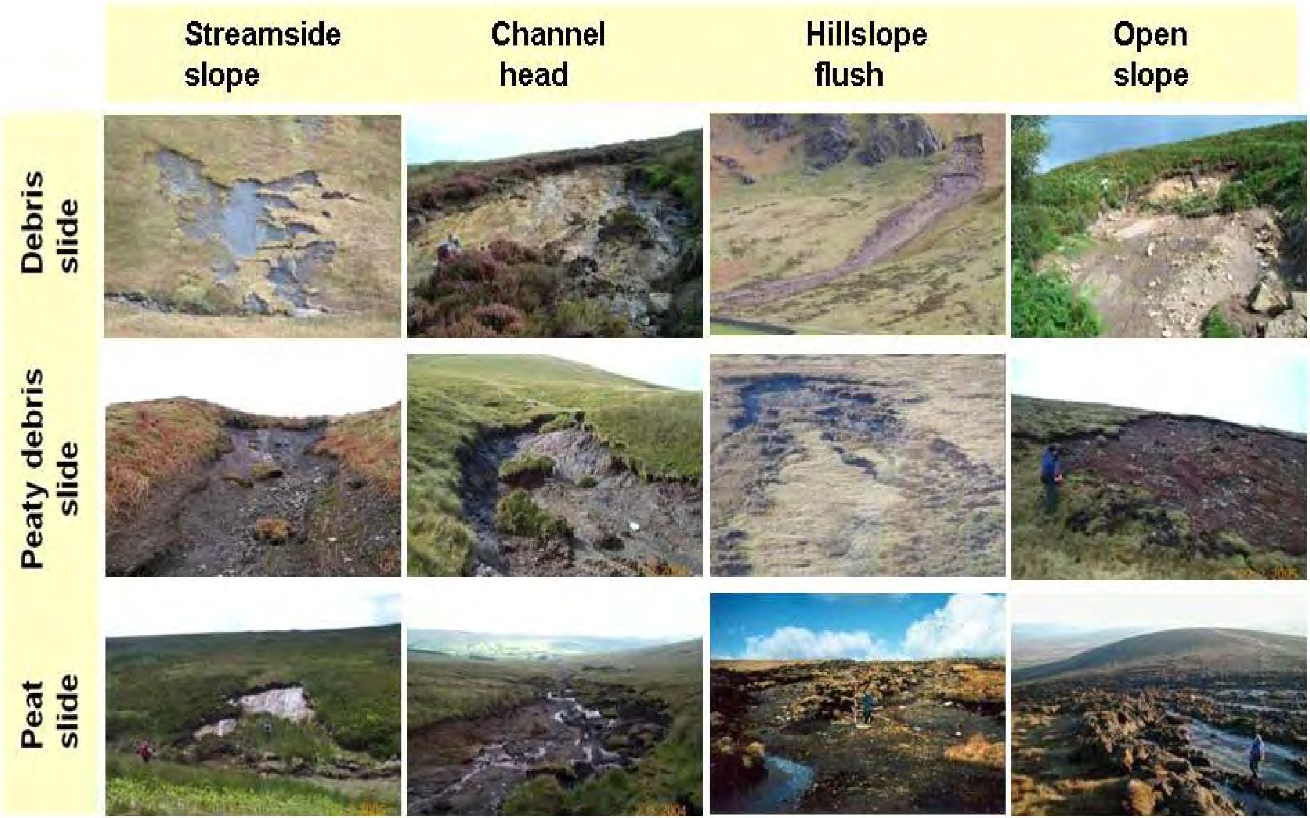


Figure 7. Typology of upland shallow landslides – based on recent British hillslope failures. The columns show the four main topographic settings and the rows show the three main material types

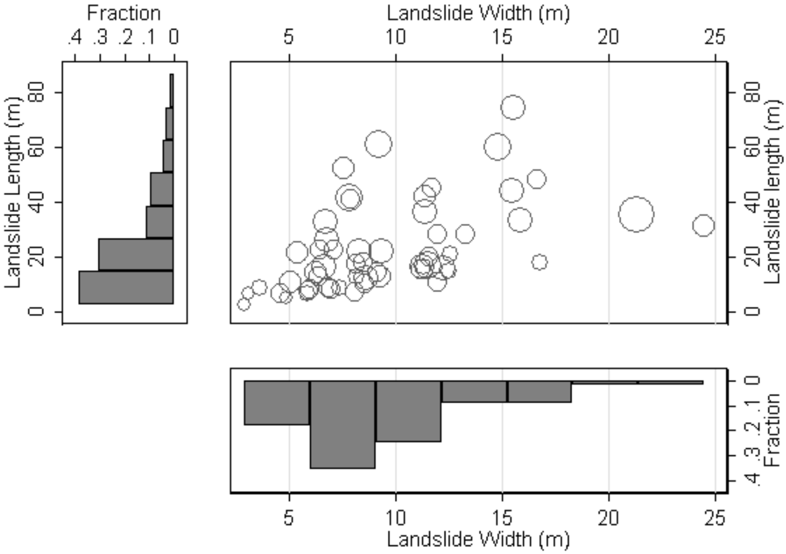


Figure 8. Morphometry of the January 2005 landslides. The graph shows landslide width plotted against landslide length with the distribution of each of these variables shown as histograms on the corresponding axes. The circles are proportional to the mean depth of each landslide measured in the scar area. Depths vary from 0.17 to 1.90 m.

Channel heads and hillslope flushes dominate as the main sources of sediment supplied to the stream network (49% of total sediment yield). A considerable amount of the sediment mobilised on the hillslopes does not enter the stream channels (3662 t or 37% of the total sediment yield). This is dominated by the failure of hillslope flushes in mineral soils with other minor failures in other slope deposits, peaty debris and even peat soils. These are relatively small isolated occurrences that in part explain why they are not well coupled to the stream system. For example, even when the failure setting is close to a stream channel (channel head or streamside) the small size of some failures means the sediment volume is insufficient to sustain a sediment transfer link to the adjacent channel (Figure 9).

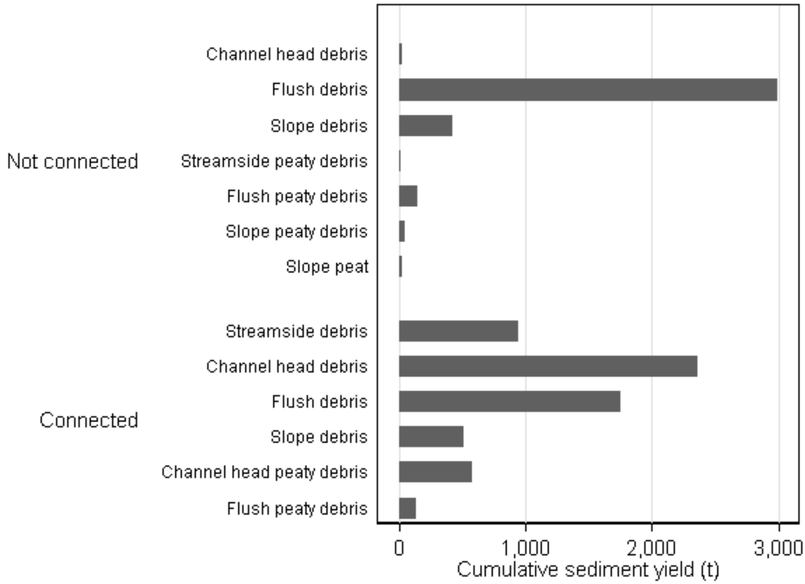


Figure 9. Summary sediment budget (cumulative sediment yield t) for the January 2005 landslides. Landslides are grouped by landslide type (see Figure 7) and whether the landslide is coupled (connected) or uncoupled (not connected) to a major stream channel.

Significance of shallow landslides

Upland and mountain headwater catchments have traditionally been viewed as active geomorphic environments with some of the highest global specific sediment yields (i.e. sediment yield per unit area) (Hewitt, 1972; Dietrich and Dunne, 1978; Church and Slaymaker, 1989; Dedkov and Moszherin, 1992; DeBoer and Crosby, 1996; Caine, 2004). Steep slopes, high runoff, widespread cryospheric activity, thin vegetation covers and active geomorphic processes all contribute to high rates of sediment production and transfer, particularly during extreme events (Johnson and Warburton, 2002a, 2002b). Detailed field studies, often within a sediment budget framework, can be used to place landslides in the context of other geomorphic events and provide estimates of their relative importance (Rapp, 1960; Dietrich and Dunne, 1978; Campbell and Church, 2003). However, without direct measurement of rates of sediment flux and estimates of coupling between hillslope and channel processes such relationships cannot be easily determined (Walling and Collins, 2000; Lawler et al., 2006).

Figure 9 provides a summary sediment budget for the January 2005 landslides in the Lake District. This suggests that a total sediment yield of 9940 t was produced during the event. Its importance can be assessed in a number of ways, but two key questions, which address contrasting timescales, are how significant is this for downstream river / lake systems; and how does this contribute to overall landscape development?

The occurrence of many of the landslides in the Bassenthwaite Lake Catchment (Figure 2) raises issues about downstream sedimentation. It has been suggested for some time now that recent increases in lake sedimentation (Cranwell et al., 1995, Bennion et al., 2000) have lead to a decline in the general ecology of Bassenthwaite Lake (Orr et al., 2004). Orr et al. (2004) and Nisbet et al. (2004) have carried out a geomorphological assessment of sediment delivery in the Bassenthwaite catchment and conclude that further research is necessary to quantify the significance of potential sediment sources. Furthermore, Thackeray et al. (2006) also suggest that the highly episodic inflows of suspended sediment into the lake may be caused by mass movements in the catchment that deliver large quantities of new sediment into the river system (Hall et al., 2001). These processes are particularly problematic in the Bassenthwaite catchment where excess fine suspended sediment concentrations have been related to decline in the Vendace (*Coregonus albula*), an endangered fish species only found in Bassenthwaite lake and Derwent Water (Atkinson et al., 1989; Winfield and Durie, 2004; Winfield et al., 2004), and also have wider implications for riverine fish (Grieg et al., 2005). In the aftermath of the January 2005 flood it was assumed that the landslides had been responsible for much of the sediment that polluted the upland water courses.

The sediment budget constructed here (Figure 9 and Table 2), based on the individual site field surveys, indicates that up to 63 % of the sediment produced by landslides enters stream courses. However, this estimate includes the full spectrum of sediment and debris sizes, not all of which can be readily transported by the stream flow. Usually it is only the fraction less than 2 mm that can be transported rapidly downstream by post-event fluvial processes. Coarser sediment remains in storage (stabilised, or undergoing only minor positional change) in the stream channel, until the next large flood mobilises these deposits (e.g. Carling & Glaister, 1987; Carling, 1997; Johnson & Warburton, 2002b; Johnson and Warburton, 2006b). Storage of landslide debris in upland stream channels is still evident at many of the study sites three years after the initial landslide events. Because of this storage effect and the considerable transmission losses of sediment in the immediate reach downstream of the landslide, due to rapid settling of coarser sediment grains (greater than 2 mm) only a small proportion (c.10%) contributes to the suspended fraction of the stream load and works its way downstream in the short-term.

In terms of the longer-term impact of the January 2005 landslides we can compare the specific sediment yield of this event (over 457 km^2) with estimates of sediment production from other Lake District fluvial sediment budget studies (Table 2).. These include the three small study catchments of Iron Crag (0.03 km^2),Wet Swine Gill (0.65 km^2), and Force Crag (0.57 km^2) which provide information on headwater sediment dynamics (Iron Crag and Wet Swine Gill), and sediment delivery to Coledale Beck within the Bassenthwaite Lake Catchment (Force Crag). The catchments have been sites of detailed sediment budget studies and are used here to illustrate catchment sediment fluxes over different timescales, for different types of event, and in settings with variable extents of man-made intervention: an annual torrent sediment budget (Iron Crag, Johnson and Warburton, 2002a); the impact of a large discrete slope failure (Wet Swine Gill, Johnson et al., 2008); and the significance of sediment supply from disused mine deposits (Force Crag Mine, Johnson and Ritchie, 2005). More recently Hopkins (2008) has provided estimates of the annual sediment yield to Bassenthwaite Lake from stream monitoring. Results suggest that the specific sediment yield from the landslide event fall within the range of yields determined from other monitoring. The value is considerably lower than the Iron Crag yield which is exceptional in that it is a highly active torrent gully system (Johnson and Warburton, 2002a, 2006 a, 2006b), but much greater than the fluvial sediment yield from the Wet Swine Gill study which is also unusual in that most of the sediment delivered to the stream channel during a hillslope failure event was stored in the channel (Johnson et al., 2008) and the Force Crag sediment budget. Interestingly the gross yield for the January 2005 landslides (6278 t) is about half that of the fine sediment (suspended load) delivered to Bassenthwaite Lake by the main input streams (Hopkins, 2008). However, bearing in mind what has been discussed in terms of in-channel sediment storage the contribution of the landslides to the fine sediment load is probably an order of magnitude less than the gross specific sediment yield reported in Table 2.

Table 2. Comparison of landslide sediment delivery with other Lake District sediment budget studies. Values are compared in terms of specific sediment yield (t km^{-2} per given time period).

Sediment production source	Sediment yield (t)	Specific sediment yield (t km^{-2})	Reference source
January 2005 landslides			
Total sediment yield [1]	9940	22	
Sediment delivered to stream channels [1]	6278	14	
Other Lake District sediment budget studies			
Iron Crag torrent sediment budget [2]	46	1916	Johnson and Warburton (2002a)
Wet Swine Gill landslide sediment budget [1]	203	3	Johnson et al. (2008)
Force Crag Mine, mineral waste sediment budget [3]	0.85	1.5	Johnson and Ritchie (2005)
Bassenthwaite catchment fluvial sediment yield [2]		51	Hopkins (2008)
UK annual upland catchment sediment yields		10 to 50	Holliday et al. (2008)
Burtness Comb rock avalanche	750000 *		Clark and Wilson (2004)

Notes:

[1] This is a single event sediment yield; [2] This is an annual sediment yield; [3] This is a 5.5 month sediment yield* Calculated assuming a rock density of 2.5 t m^{-3}

Furthermore if we consider the role of shallow landsliding in relation to other mass movements, for example the historic rock avalanche deposit in Burtness Comb (Clark and Wilson, 2004), then it is clear that the yield from the January 2005 is several orders of magnitude smaller than those from these large rock slope failures (Wilson et al., 2004). However, these comparisons must be treated with great caution because of the subjectivity in selecting an appropriate area for the calculation of the specific sediment yield. For example although the landslide contribution was assessed for the research area as a whole a more valid comparison with the smaller scale catchment studies would be to assess the landslide sediment delivery at the local sub-catchment scale for single or local clusters of landslides.

Conclusion

This paper has presented initial results from an inventory of landslides that is novel in its level of detail and completeness. The location of individual slides is strongly influenced by local factors; the emergent patterns over the full study area appear closely related to both the track of the January 2005 storm cell and the area's solid geology. A physical explanation for the latter invokes the geological control on the landscapes topographic form and material properties, which in turn control its stability. Although specific locations and triggers may differ considerably, the Lake District's landslides have morphometric characteristics in common with observations from other parts of Britain and our landslide typology provides a useful framework within which to compare such events. Finally, the simple, sediment budget analysis has shown that the shallow landslides provide a relatively small contribution to the overall suspended sediment load and given that they occur only in extreme events are unlikely to be of major long term significance to the catchment sediment flux. It is important to recognise that from a global perspective UK upland and mountain catchments have relatively low rates of geomorphic activity and small sediment yields (typically 10 to 50 t km^{-2} yr^{-1} (Table2; Ledger et al., 1974; Holliday et al.,2008)). In other geomorphic settings shallow landsliding is of greater significance (Dietrich and Dunne, 1978; Hovius et al., 1997). Nevertheless, from a local perspective erosion is remains a significant problem and needs to be effectively managed.

Acknowledgements

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