Catena 127 (2015) 152–169

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Sediment erosion dynamics of a gullied debris slide: a medium-term record

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ARTICLE INFO

Article history:
Received 13 August 2014
Received in revised form 7 December 2014
Accepted 9 December 2014
Available online 9 January 2015

Keywords:
Headwater catchment
Debris slide
Medium-term sediment dynamics
Erosion
Gully development
Meteorological conditions

ABSTRACT

Medium-term post-event sediment flux investigations are rare for headwater catchments and particularly sparse for gullied hillslope failures. Repeat field observation, ground photography and cross section measurements of a debris slide scar at the Wet Swine Gill headwater catchment (0.65 km^2) in the English Lake District (UK), provide evidence of erosion and deposition dynamics over the medium-term (2002–2014). These data are compared to site topographic and meteorological conditions, to evaluate potential process–response linkages.

Rill and gully erosion networks establish soon after the slide failure (1 February 2002); thereafter gully enlargement proceeds rapidly, first by vertical downcutting, prior to lateral expansion and gully wall angle decline. Changes in cross sectional width, depth and area (2002–2013) are characterised by statistically significant ($P = <0.05$) negative exponential growth models (R^2 = width: 0.88–0.97; depth: 0.71–0.86; area: 0.87–0.93). Gully walls were dominated by erosion but the gully bed was characterised by episodic sediment production, storage and transfer often leading to temporary deposition. Specific erosion rates on the gully wall exceeded those on the adjacent slide scar by up to 764% (maximum values = wall: −0.0084; scar: −0.0011 $m^2\ m^{-1}\ d^{-1}$). Upslope contributing (runoff) area and slope gradient are generally important for erosion; although linear regression analysis demonstrates weak or insignificant relationships between meteorological conditions and gully/scar sediment flux. A general conceptual model of slide scar evolution, integrating gully growth and capture, summarises activity at this site. However transferability to locations with terrain characteristics, land management practices and climate conditions different to those existing in the UK uplands remains to be tested. This investigation adds to growing appreciation of the complexities of sediment dynamics in headwater catchments and provides clear evidence for the potential of early management intervention to counter detrimental post-failure sediment erosion; which at this site would have been most effective up to 3–4 years following gully initiation.

1. Introduction

Catchment headwaters are important for sediment production, storage and transfer (Benda et al., 2005; Gomi and Sidle, 2003; May and Gresswell, 2003). This is due to a combination of their steep gradients, high runoff, often fragile vegetation and range of active geomorphic processes (Kasai, 2006; Warburton, 2010; Wohl and Merritt, 2008). Developing a clear understanding of headwater geomorphological and hydrological processes offers significant environmental and economic benefits. For example, high sediment yields can detrimentally impact ecological, water and soil resource status; impact infrastructure; and create hazard and risk conditions (Johnson et al., 2010). Process knowledge is also required to model how sediment cascades will respond to predicted climate change, which in turn helps develop sustainable land management strategies.

Conceptual sediment budget frameworks for upland/mountain systems (Dietrich and Dunne, 1978; Warburton, 2010) identify hillslope and channel locations as key landscape elements. Episodic mass movements from hillslopes can be the dominant sediment source for adjacent channel networks; however, these hillslope to channel coupling relationships are complex. For example, Johnson et al. (2010) and Warburton (2010) demonstrate that upland sediment dynamics are influenced by the specific geomorphic processes present in respect of their magnitude, frequency and spatial distribution. However, understanding of such processes is often governed by the timing, longevity and spatial extent of a geomorphic investigation. Considering both these factors it is now increasingly recognised that in order to better understand headwater sediment systems it is necessary to investigate not only the episodic hillslope failures, but also the post-failure process response (Hovius et al., 2000; Johnson et al., 2010; Korup, 2009; Nakamura et al., 2000). Following this theme a number of landslide studies have evaluated post-failure sediment supply and the characteristics of vegetation and soil recovery on scar areas (Guariguata 1990; Imaizumi et al., 2008; Larsen et al., 1999; Lin et al., 2006; Smale et al.,

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http://dx.doi.org/10.1016/j.catena.2014.12.018
0341-8162/

1997; Sparling et al., 2003). Furthermore, landslide scars and deposits often provide sites for subsequent gully development (Marden et al., 2012; Menéndez-Duarte et al., 2007; Parkner et al., 2006; Valentin et al., 2005; Warburton and Higgitt, 1998). However, very few studies have investigated the significance of gullies in such locations; exceptions being Johnson et al. (2010) and Larsen et al. (1999) who identify gullying of landslide scars to be an important post-failure sediment production and transfer process. For example, at Wet Swine Gill in the northern Lake District (UK), Johnson et al. (2010) demonstrate that scar erosion in the six years after failure was of greater magnitude than that which occurred at the time of slope failure. Further, during the period June 2003 to January 2004, c. 98% of net scar erosion was via gullying.

Gully form varies depending on the geographical (e.g. agricultural fields, alluvial valley floors, lake margins and catchment headwaters) and climatic settings in which gullies exist (Kirkby and Bracken, 2009; Poesen et al., 2003; Valentin et al., 2005; Vandaele et al., 1996). Poesen et al. (2003) outline a continuum of incised forms, varying between small-scale rills to river channel erosion, and includes ephemeral and permanent (or classical) gullies (Bracken 2010; Casalí et al., 2009; Gang et al., 2009; Poesen et al., 2003; Vandaele et al., 1996). Permanent gullies, are typically characterised as deep (>0.5 m) and narrow channels with steep sidewalls on a hillside; are too large to be obliterated by tillage and therefore persist; have visible erosion and headcuts; and develop through a combination of fluvial and mass wasting processes (Kirkby and Bracken, 2009; Poesen et al., 2003; Vandaele et al., 1996).

The objectives of this investigation are: to document and assess changes to the debris slide scar and gully form over the period 2002–2014 (i.e. a medium-term, defined by Marzolff et al., 2011, as 5–15 years); and to consider the short-term linkages between meteorological conditions and sediment system behaviours. The paper contributes to advancing understanding of headwater sediment dynamics, using a case study of a hillslope failure scar at Wet Swine Gill, UK. The project benefits from an extended monitoring programme which has been carried out at this site (Johnson et al., 2008, 2010) which provides an excellent opportunity to investigate the impact of post-failure debris slide scar gullying, in more detail than hitherto reported.

2. Wet Swine Gill catchment

Wet Swine Gill (Lat. 54°41′N, Long. 3°04′W) is a first order tributary (catchment area 0.65 km^2) of the River Caldew located in the Skiddaw Massif, Lake District, Northern England (Fig. 1 A & B). Catchment elevation ranges between 307 m and 660 m OD, with a mean main stream slope of 0.18 m m^{-1}. Annual precipitation is not monitored directly at the site but is assumed to be similar to that at Iron Crag (2 km NW, 576 m OD.) (Fig. 1 B), and is approximately 2200 mm (annual mean 1999–2004) (Johnson and Warburton, 2003; 2006).

Skiddaw Group Ordovician siltstones and mudstones (British Geological Survey, 1997; Jackson, 1978) principally underlie the catchment, with a minor intrusion of dolerite of mid or post Ordovician age (British Geological Survey, 1997). The entire area is within the metamorphic aureole of the Skiddaw Granite probably of Lower Devonian age (British Geological Survey, 1997; Clark and Wilson, 2001; Firman, 1978; Fortey et al. 1984; Shipp, 1992). Fortey et al. (1984) report the outcropping of a quartz–antimony bearing vein in Wet Swine Gill, but no evidence of metal mining exists (Cooper and Stanley, 1990; Day, 1928). The absence of mining is significant, as this type of historical land use has widely impacted other headwater streams in the Skiddaw Massif (e.g. Cooper and Stanley, 1990) and consequently altered their long-term sediment dynamics.

During the Quaternary the Lake District landscape was subject to temperate (interglacial), glacial (ice sheet) and periglacial/restricted glacial (cirque/valley glaciers) environment processes (Boardman, 1992). For example, in the immediate surrounds of Wet Swine Gill, Evans (1994) considers Mosedale to be a glacial trough ('1' on Fig. 1 B), and Clark and Wilson (2001) suggest debris ridges below Ling Thrang Crags ('2' on Fig. 1 B) to be a terminal moraine from a Loch Lomond Stadial (LLS, c. 11–10 ka BP) glacier. Whilst Bowscale Tarn ('3' on Fig. 1 B) is widely recognised to be a former cirque basin last occupied by glacial ice during the LLS (Clark and Wilson, 2001; Evans, 1994; Sissons, 1980). However, Boardman (1992) argues that the prevalence of restricted glacial conditions during the Quaternary in the Lake District (c. 60% of the time since 128 ka BP) means the greater landscape legacy is from periglacial processes; most particularly during the LLS, when frost weathering and snowmelt produced extensive frost-shattered slope deposits from susceptible Skiddaw Group rocks. In many places these debris mantles remain in-situ (Boardman, 1992), and therefore provide large hillslope sediment sources for contemporary geomorphic process activity.

The overlying soils in the catchment are a mosaic of raw oligo-fibrous peat and lithomorphic humic rankers (Soil Survey of England and Wales, 1983). Vegetation is heather (*Calluna vulgaris*) and bilberry (*Vaccinium myrtillus*) dominated moorland heath with broadleaved woodland in adjacent streams (LDNPA, 1997) and bracken (*Pteridium aquilinium*) at lower elevations. The heather moorland habitat is managed using controlled burning, especially in the Cocklakes area (LDNPA, 2001, 2002; Ratcliffe, 2002) (Fig. 1 C).

In common with many UK upland catchments, management has altered the drainage network, resulting in a change to the catchment area. Between October 1997 and July 2004 the effective catchment area, 0.65 km^2, comprised a natural watershed (0.41 km^2), with additional water capture from the adjacent stream system (Burdell Gill, 0.13 km^2) and intervening hillslope (Cocklakes, 0.11 km^2) (Fig. 1 C). This catchment expansion was associated with the restoration of an artificial irrigation channel (Eastham, 2002, personal communication). However, in July 2004 the drainage channel was permanently infilled in order to reduce runoff to the slide scar, where significant gully erosion had occurred following a debris slide in 2002 (Fig. 1 C & D; Standring (2004) personal communication). The motivation for the drainage channel blocking was that the eroded sediment was of concern to local stakeholders and statutory authorities due to the potential adverse downstream impact on habitat.

3. 2002 Hillslope–channel sediment transfer

The 1 February 2002 Wet Swine Gill event consisted of an unconfined translational debris slide that ran out directly into the adjacent downslope stream channel. Momentum carried the failure body up the opposite valley side, which then transformed into a channelised debris flow downstream. Evidence of the debris flow could be traced 279 m downstream before abruptly translating into a fluvial flood which eroded the stream channel for another 338 m before finally discharging into the River Caldew confluence (Fig. 1 B & C). Johnson et al. (2008, 2010) provide a detailed description and analysis of this event, in respect of its timing, cause, impacts and event dynamics. The key factors which caused the failure/flow included alteration of the local hydrological drainage network increasing potential runoff, vegetation burning and a rainfall event on 1 February 2002. Johnson et al. (2008) report the resulting slide scar is located between 500 and 485 m OD., on a steep slope (0.58 m m^{-1} or 30°); of dimensions 22.3 m wide, 31.3 m long and 181.1 m^3 initial erosion volume.

The Wet Swine Gill hillslope failure is typical of many hillslope failures throughout Northern England. For example, in the Lake District, Warburton et al. (2008) discuss the spatial distribution, controls, failure morphometry and sediment yield of 62 landslides within a 457 km^2 study area (Bassenthwaite Lake catchment and Skiddaw Massif), which occurred in response to the 7–8 January 2005 storm. More recently 16 failures (observed by the authors on 10 July 2012) occurred only 5.5 km SW from West Swine Gill on Blease Fell and Lonscale Fell (Fig. 1 B & E); some transferred sediment and vegetation debris to