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

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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 km2) 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 (R2= 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 m2 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 remain 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.

REVISION NOTES

Manuscript: **CATENA 3594**
Manuscript Title: Sediment erosion dynamics of a gullied debris slide: a medium-term record.
Authors: Richard M Johnson & Jeff Warburton

Review Summary:
The manuscript is very well written. The authors introduce the material and describe the measurements very clearly. The analysis of the results and the discussion are clear and concise. Overall, the manuscript is ready for publication. Minor suggestions and comments follow.

Thank you, very kind comments

Specific Comments:
Additions- yellow shade; deletions- no shade

- Please look at all lists within the text. In some lists, a comma follows the last item prior to the "and", and in others, no comma follows the list item. Please make them all the same. Actioned, removing ‘,’ prior to ‘and’- where judged relevant (i.e. all list cases, and some sentence structure locations, except where remains useful): p2L5; p4L10/20; p5L5/21; p9L23; p11L1/5; p12L4/16; p14L3/6/20; p16L14/15; p17L10/11; p18L9/13/17/19; p19L17; p20L11/13/15/18; p22L18; p23L15; p24L20; p25L14/22; p28L17/22; p30L2/8; p31L4; p32L21; p33L13
- P4L20: Insert "that" following "demonstrate". Actioned
- P11L2: Insert ", where" following "April 2008)". Actioned
- P13L13: Insert "," following "contrast". Actioned
- P15L2: Insert "," following "data". Actioned
- P15L8: Insert "," following "consequence" and change "," to ";" following "markedly". Actioned *2
- P15L9: Insert "," following "example". Actioned
- P15L10: Insert "," following "2004" and delete "," following "rapid". Actioned *2
- P15L15: Insert "," following "2004" and "Here". Actioned *2
- P17L6-12: Perhaps try … Measurement errors were minimized according to a rule set throughout the study period that included: keeping the … Actioned: Original text deleted and new phrase added, with UK spelling of ‘minimised’ so consistent with wider none use of ‘z’
- P18L10: Delete "also". Actioned
- P18L11: Insert "," following "general". Actioned
- P18L12: Change ";" to ",". Actioned
- P18L22: Insert "," following "erosional". Actioned
- P18L24: Delete ", ranging". Actioned
- P19L5: Insert "," following "Additionally". Actioned
- P19L10: Insert "on" following "rates". Actioned
- P27L23: Insert "," following "Gill". Actioned
- P28L21: Change "it" to "is". Actioned
- P36L7: Casali should have an accent on the i. Both here and in the text. Actioned, including p6 L1
- P41L8: Please check reference. Text has "Met." And reference is "Met". Actioned, so reference and text identical/ correct as: ‘Met.’

- P44L6: Reference is not mentioned in the text. Vandekerckhove et al., 2000. No change- ‘2000’ is cited p23L10-11
- Please check the style of the reference section. Consulted the author information pack- No specific guidance apparent for the scenario where the cited author is an organisation, hence follow the example here and remove ‘.’ following organisation names P36L1 "British Geological Survey.,"? Should the "." Be included here. Actioned Similar references are P39L16, Actioned P41L8 Actioned, P42L1 Actioned, and P43L4 Actioned.
  Also P40L5,L7, L10 actioned
- Please check the style for the use of the ampersand (&) with regard to references within the text Actioned- In text references- ‘and’ used instead of ‘&’ to conform with the style in the author information pack. All locations highlighted.

Additional actions

1. Figure 3- changed date format to use ‘/’ so more consistency in date formats
2. Table 1 A- changed date format to use ‘/’ so more consistency in date formats
3. Table 2 A- changed date format to use ‘/’ so more consistency in date formats
4. Figure 4- changed date format to use ‘/’ so more consistency in date formats

***Highlights (for review)**

- Post-failure erosion is three orders greater on gully walls than the slide scar
- Erosion is more influenced by local topography than by meteorological conditions
- Gully width, depth & area development characterised by a negative exponential model
- Gully evolution has three phases: incision, width increase & wall angle decline
- Early intervention, up to 4 years post-failure, is important to reduce erosion

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

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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.

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KEY WORDS: headwater catchment; debris slide; medium-term sediment dynamics; erosion; gully development; meteorological conditions.

1.0 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 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., 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 program 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.

2.0 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 (Figure 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.) (Figure 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 Figure 1 B), and Clark and Wilson (2001) suggest debris ridges below Ling Thrang Crags (‘2’ on Figure 1 B) to be a terminal moraine from a Loch Lomond Stadial (LLS, c. 11-10 ka BP) glacier. Whilst Bowscale Tarn ('3' on Figure 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) (Figure 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) (Figure 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 (Figure 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.

3.0 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 (Figure 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 500-485 m OD., on a steep slope (0.58 m m^{-1} or 30 degrees); 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 (Figure 1 B & E); some transferred sediment and vegetation debris to Glenderaterra Beck. These slope failures coincide with a rainfall event on 22-23 June 2012 (Barron, 2012, personal communication; Met. Office, 2013), for which 93.8 mm was recorded at the Blencathra Centre (1.5 km SE of Glenderaterra Beck, Figure 1 B) (Keswick Reminder, 2012). These frequently recurring instances of hillslope failure continue to pose questions about the significance of hillslope sediment supply and transfer to sensitive downstream rivers and lakes (*cf.* Warburton, 2010) and are of considerable concern for local land management agencies.

4.0 POST- FAILURE SEDIMENT MONITORING PROGRAMME

Johnson et al. (2010) outline adjustment of the failed hillslope and adjacent Wet Swine Gill stream channel during the period 2002-2008. Using a multiple sediment budget approach (2002 [failure], 27 June 2003- 5 January 2004 and April 2008) where they examine the changing nature of failure and post-failure sediment dynamics. The key finding was a switching in the main source of sediment delivery from hillslope sources at the time of the failure (2002), followed by reworking of deposited channel sediments (2003-2004) and then (2008) a return to hillslope sediment supply.

In the present study, we examine in detail slide scar development and gullying using new data, which provide a longer, novel perspective on hillslope adjustment, and greater spatial resolution for the critical period 2003-2004 when erosion was amongst the most active. Data consist of: repeat photography from a fixed ground marker (2002-2014) (FPP 1 in Figure 2); repeat measurement of 'medium-term' monumented cross sections across the entire scar (2002-2013) (Figure 2); repeat measurement of 30 smaller 'short-term' monumented cross sections distributed across the drainage channel (n= 4), main gully (n= 11), and slide scar (n= 15) (June 2003- January 2004) (Figure 2). The impact of ground surface temperature fluctuations (at Wet Swine Gill) and rainfall variability (at Iron Crag) on sediment dynamics are analysed.

5.0 MEDIUM-TERM SLIDE SCAR DEVELOPMENT (2002-2014)

5.1 Ground-based photography & field observations

Twenty-one repeat photographs provide a qualitative record of hillslope development between 17 June 2002 and 30 July 2014 (12.12 years), with intervals ranging between 15 and 812 days (Figure 3 shows key images). Incision began soon after the exposure of the scar area; being well established by 17 June 2002. Initial development involved the formation of multiple (*n*= 6), linear and parallel rills/ gullies. Between August 2002 and April 2003 significant expansion of the rill network occurred, creating one main gully. The headward erosion of the main gully captured the drainage channel, thereby re-directing all the flow from drainage channel to Wet Swine Gill via the slide scar (Figure 1 C). The morphology of the main gully remained relatively stable until at least January 2004, although by June 2004 significant widening at the gully head and a reduction of the gully wall angles towards the base of the eroded hillslope were observed. Following deliberate permanent blocking of the drainage channel at the head of the slope (18-21 July 2004), gully development slowed with only minor widening and a small reduction of gully wall angles. By March 2008 (and thereafter) continued headward recession in the vicinity of the drainage channel, resulted in undermining of the former drainage channel bed and undercutting of the adjacent hillslope as shown by the overhanging vegetation.

Post-failure activity beyond the main gully was initially less marked, but became more prominent by 2008. The ‘left gullies’ (Figure 3) can be grouped into two sets, firstly shallow forms which existed prior to June 2004 and were captured by the widening of the main gully and; secondly, two gullies which developed nearer the scar edge (‘new left gullies’ in Figure 3), fed by runoff from the upper hillslope. By March 2008 these gullies transferred sediment beyond the scar perimeter, with coarse sediment eventually coupling with Wet Swine Gill (first observed in July 2012). Furthermore, ongoing interfluve lowering between them (Figures 3 and 4), may in time result in the capture of gully L1 by gully L2. These may also eventually merge with the main gully, triggering a new phase of activity.

Natural re-vegetation of the scar surface has been slow and localised. Heather (*Calluna vulgaris)* regrowth is most prominent on areas of degraded organic soil blocks; which are remnants of the former burnt peat surface not exported from the scar at the time of failure. These observations are consistent with previous observations which demonstrate that following fire heather will regenerate from basal stems and surviving seedbanks (e.g. Backshall et al., 2001; Gilchrist et al., 2003). In contrast, the exposed mineral soil surface is taking longer to recover, probably due to the loss of the overlying soil and pre-existing biological communities (e.g. Geertsema and Pojar, 2007; Gilchrist et al., 2003), combined with ongoing gully erosion which inhibits vegetation establishment (Imeson, 1971). However, observations from August 2009 identify the natural development of sparse/ juvenile grass and heather adjacent to the scar margin, i.e. the areas of greatest stability and closest proximity to existing seed banks. In response to this situation, Natural England and the Lake District National Park Authority (LDNPA) planted 150 Juniper shrubs (*Juniperus communis*) across both the scar (*n*= 120) and the surrounding pre-failure ground surface (*n*= 30) on 11- 12 March 2010 (Figure 3, photo 6). This experiment aims to promote slope stability and reduce sediment flux (Standring, 2010, personal communication). Figure 3 (photos 7 & 8) shows subsequent widespread loss/ tilting of the plastic nursery guards installed around the Juniper shrubs. By 30 July 2014, 39% of nursery guards had failed and only 30% of the planted shrubs were established. Furthermore, following February 2014, under a 2013 Higher Level Stewardship Agreement, the Caldbeck Commoners Association, LDNPA and Natural England, have planted 500 native trees on hillslopes adjacent to the Wet Swine Gill stream, with 64 immediately downslope of the scar (Barron, 2014, personal communication; Planning Inspectorate, 2014). Additional works are planned for later in 2014, including a temporary fence enclosure (consented for 15 years) around the failure scar (Barron, 2014, personal communication); this is part of a wider initiative in the Caldbeck Fells to reduce sediment transfer and improve water quality (Planning Inspectorate, 2014).

5.2 Cross section measurements (2002-2013)

Two monumented cross sections across the scar area (Figure 2) were resurveyed ($n = \leq 8$ occasions) between 12 August 2002 and 7 July 2013 (Table 1 A and Table 2 A). Measurements were obtained using an automatic level and stadia staff (2003 & 2004); or inclined tape line, clinometer and measurement rule (2002 and 2008 onwards).

Figure 4 shows the evolution of the scar surface at the top and base of the slope. This demonstrates that scar width has remained relatively stable since the hillslope failure, with significant change being focused on the scar surface.

Table 1 and Figure 4 show the growth of the main gully (as also outlined in Figure 3). Based on these data, four key observations standout; firstly, between August 2002 and June 2003 a rapid transition of main gully size and shape occurred. Gully area percentage change (%Δ, as defined in Table 1) increases at the two cross sections, ranging 105% (0.68 to 1.39 m^2) to 797% (0.21 to 1.84 m^2). This enlargement is dominated by vertical incision (e.g. 0.16 to 1.47 m at top cross section) accompanied with minor lateral growth (e.g. 2.10 to 2.20 m at base cross section). As a consequence, width-depth ratios reduce markedly; for example, at the top cross section from 17.8 to 1.4. Secondly, between June 2003 and March 2004, change was much less rapid and lateral expansion of the main gully became more important than vertical incision; where gully-top width percentage changes for the top and base of scar cross sections are: 125% (2 to 4.5 m) and 59% (2.2 to 3.5 m) respectively, contrasting depth changes of 12% (1.47 to 1.64 m) and -2% (0.9 to 0.88 m) respectively. Thirdly, following 2004, changes at the top cross section slowed considerably. Here, gully width increased from 4.50 m in 2004 to 5.35 m in 2012, with percentage change between successive surveys being generally less than 10%; an accompanying trend towards sediment infilling is reflected in reducing depths (1.64 m in 2004 to 1.42 m in 2013) and reducing area following a peak size of 4.80 m^2 in 2009 to 4.23 m^2 in 2013. The gully shape in this period showed relative stability where width-depth ratios are low and evolving from around 3 to 4. Fourthly, the main gully in the base cross section in the period following 2004, has constantly increased in width but with diminishing magnitude of percentage change: 49% (2004-2010), 8% (2010-2012), 1% (2012-2013); an initial sediment infilling phase 2004-2010 of -35% (2.21 to 1.44 m^2) has since reversed indicated by depth and area increases, with percentage change between surveys not exceeding 15% and 20%, respectively. The gully width-depth ratio is variable, ranging from 4 to 10.4 since 2004, but becoming more stable following 2010, between 9 to 10.

Figure 4 and Table 2 also show the change in the two ‘new left gullies’. They evolve in a similar pattern to the neighbouring main gully (top cross section). This includes four key observations. Firstly, in the period March 2008 to November 2009 the combined area of both gullies increased by 43% (0.65 to 0.93 m^2). A slightly greater proportion of this growth is accounted for by depth increase (23 to 30%) rather than width increase (9 to 22%). Secondly, from 2009 onwards growth in width is sustained, albeit with declining rates of growth (8 to 0 % at L1 and 39 to 4 % at L2). Thirdly, following initial increases in depth (up until 2009 for L1 and up until 2012 for L2), sediment infilling is particularly noticeable, up to a -26% reduction in depth (0.37 to 0.28 m) at L1 in the period 2012-2013. A corresponding reduction in the total area of both L1 and L2 occurs following 2010 (1.14 m^2 to 1.04 m^2). Fourthly, gully width-depth ratios, whilst similar to the main gully, are typically more dynamic in the short-term, here they range 2.1 to 5 for L1 and 2.8 to 4.3 for L2. This increased sensitivity may reflect the different scales of the gullies relative to grain size which comprises the sedimentary infill i.e. a single large boulder can have a large influence on form in the smaller gullies.

6.0 SHORT-TERM SLIDE SCAR DEVELOPMENT (2003-2004)

6.1 Monitoring method

The 30 short-term cross section (XS) profiles were measured on up to 14 occasions, at an interval of approximately 14 days (range: 10- 26 days), using an inclined tape (width) and measurement staff (depth). Measurement errors were minimised according to a rule set throughout the study period that included: keeping the tape taught, fixing the tape at a standard elevation on the end-point monuments, avoiding adverse weather (wind, snow covered ground), reading the depth on the top of the inclined tape and taking measurements at set intervals along the tape (0.1 m for XS 1-15 and 0.25 m for XS 16-24, Figure 2). A subsequent data validation exercise removed anomalous data, providing 346 profile comparisons (from a maximum of 390). These data determine the net change in cross sectional area (m^2) at a profile location, between two points in time (i.e. a monitoring interval, t_i to t_{ii} etc.), with change partitioned into drainage channel/ gully wall and bed elements for XS 1-15 (Figure 2). Where changes are either net erosional (sediment production > sediment storage) or net depositional (sediment production < sediment storage).

6.2 Drainage channel, main gully & scar surface cross sectional dynamics (June 2003- January 2004)

Detailed understanding of the spatial and temporal characteristics of sediment dynamics in these geomorphic components of the debris slide/ gully system are provided by standardised process rate data, which allow for the variations in cross section bed/ scar width or wall height (i.e. unit distance). Derivatives of net area per unit distance (m^2 m^{-1}) are used in Figures 5 and 6; where Figure 5 shows spatial variations over the entire 2003-2004 period and Figure 6 depicts cumulative behaviour over time (i.e. monitoring intervals comprising the 2003-2004 period). Further, Figure 7 shows specific process rates in m^2 m^{-1} d^{-1}.

Figure 5 shows the net area per unit distance change aggregated over the entire 2003-2004 period (Σ m^2 m^{-1}), with partitioning into geomorphic components (i.e. drainage channel, main gully, slide scar) and wall and bed elements for XS 1-15. In general, the main gully (XS 5-15) is most active, followed by the drainage channel (XS 1-4), with the least activity on the slide scar (XS 16-24). In Figure 5 (A) cross sections 5-10 all have gully wall erosion rates exceeding -0.2 m^2 m^{-1} (range: -0.22 to -0.54 m^2 m^{-1}) and gully bed deposition of variable and sometimes greater magnitude (range: 0.02 to 1.27 m^2 m^{-1}). This spatial extent of more active gully wall erosion and gully bed deposition (see Figure 2 for locations) corresponds with that previously described as experiencing headward erosion by April 2003 (Figure 3) and gully enlargement principally through width expansion between June 2003 and March 2004 (Figure 4 Top XS and Table 1). Above (XS 1-4) and below (XS 11-15) the area of active head cut, process rates are typically less (maxima: -0.23 m^2 m^{-1} [wall] and 0.38 m^2 m^{-1} [bed]), and dominantly erosional, probably reflecting reduced wall sediment supply. Figure 5 (B) shows lower process rates which are typically erosional (0.04 to -0.10 m^2 m^{-1}). In this area of the debris slide scar, there are slightly increasing erosion rates downslope (i.e. XS 17 to 19 and XS

24 to 22). This pattern is consistent with areas susceptible to erosion by overland flow, due to increasing scar slope angles prior to cross section locations (XS 17 & 18 [30° & 35°] & XS 23 & 22 [29° & 33°]), and increasing contributing flow area downslope (both are shown by Figure 2). Additionally, these patterns may also reflect differences in material properties, although there are currently insufficient data at this site to explore this hypothesis. Secondly, a depositional toe deposit occurs after XS 22, this corresponds with a local reduction in gradient (XS 24- 22: 0.63 m m^{-1} [32°], XS 21-20: 0.49 m m^{-1} [26°]). Thirdly, the differences in erosion rates on either side of the gully are slight, albeit the left side of the gully is more active (-0.03 to -0.10 m^2 m^{-1}) than the right side (-0.01 to -0.04 m^2 m^{-1}).

Figure 6 shows the cumulative change over time in net erosion and deposition in geomorphic components. These data are based upon an average (mean m^2 m^{-1}) from multiple cross section locations, as grouped in Figure 2. Figure 6 clearly shows the greatest change in the main gully and least change on the slide scar. The overall trends are net scar erosion, net wall erosion and net bed deposition. In particular, Figure 6 (A) shows the dominant cumulative behaviour for walls is erosional and beds depositional; where the latter are typically of greater magnitude. Secondly, the drainage channel and main gully walls have similar cumulative rates of erosion until 12 November 2003 (up to c. 0.1 m^2 m^{-1}), thereafter increasing gully wall erosion is particularly marked (up to 0.33 m^2 m^{-1}). Thirdly, drainage channel and gully bed behaviours are more divergent in terms of both the direction of cumulative change (i.e. phases of storage gain and depletion) and the relative magnitude between each. Figure 6 (B) clearly demonstrates lower process rates on the scar area, and a weak tendency to net erosion by the end of the study period.

Figure 7 shows the change in specific process rates over time (mean m^2 m^{-1} d^{-1}) in geomorphic components. Figure 7 supports the overall trends shown in Figures 5 and 6, but also identifies three pronounced erosional phases in the main gully walls and frequently the bed (Figure 7(A)). These are monitoring intervals: (1) 25 July to 8 August 2003 (wall: -0.002 m^2 m^{-1} d^{-1}; bed: -0.004 m^2 m^{-1} d^{-1}), (2) 5 to 19 September 2003 (wall: -0.002 m^2 m^{-1} d^{-1}; bed: -0.003 m^2 m^{-1} d^{-1}) and (3) 10 December 2003 to 5 January 2004 (wall: -0.008 m^2 m^{-1} d^{-1}). These time intervals coincide with episodes of increased wetness (Table 3), particularly shown by higher maximum 1-hour rainfall intensity (9.1, 4.8 and 6.4 mm h^{-1}, respectively). Johnson et al. (2010) also identify the same July to August 2003 and December 2003 to January 2004 intervals, in respect to significant increments in gully sediment yield. Figure 7 (B) shows slightly increased rates of erosion (up to -0.001 m^2 m^{-1} d^{-1}) across the entire scar, on three occasions: (4) 5 to 19 September 2003, (5) 19 to 29 October 2003 and (6) 10 December 2003 to 5 January 2004. So there is reasonable similarity to the timing of pronounced erosional phases in the main gully.

7.0 DISCUSSION OF POST- FAILURE SLIDE SCAR DEVELOPMENT

The preceding sections detail the characteristics of slide scar/ gully change at Wet Swine Gill over 12 years. Findings can be summarised into four key observations. Firstly, gully evolution exhibits distinct behaviours in respect to both timescale and adjustment of form. Initially main gully growth is rapid, comprising coalescence of rills and headward extension, and thereafter rates of gully change typically slow over time. Gully change is initially dominated by vertical downcutting followed by greater width expansion and gully wall angle decline. Secondly, in respect to the main gully, walls tend to be erosional, and the bed dominantly depositional; with bed locations typically showing higher process rates than those occurring on the gully walls. Thirdly, highest rates of geomorphic change are associated with drainage channel/ gully features, rather than the spatially more extensive scar surface. Finally, variations in erosion/ deposition rates are influenced by rainfall, scar contributing runoff area and slope gradient.

7.1 Gully evolution: initiation

A number of studies suggest that gully initiation can occur soon after landscape disturbance. For example, Prosser and Soufi (1998) in reference to slopes near Bombala, New South Wales, Australia, identify gully initiation within one year of intensive forest clearance. Similarly, Warburton et al. (2003) in discussion of the February 1995 Hart Hope peat slide in the North Pennines, UK, identify fluvial gully development soon after the failure. Prosser and Soufi (1998) suggest that this early onset of gullying reflects an increased environmental susceptibility (i.e. high erodibility) following soil disturbance and degradation of vegetation covers. These exposed ground surfaces may then be subject to formative rainfall-runoff events (i.e. events of high erosivity) that exceed the surface erosional resistance. They suggest that in the Bombala case resistance to channel initiation recovers within a year of disturbance, through vegetation regrowth, soil compaction and increased infiltration; although where gullying has begun, this acts to inhibit recovery thereby maintaining susceptibility to erosion. It is therefore important to determine where and why gullying develops. In this respect, Poesen et al. (2003) and Valentin et al. (2005) consider the following to be the key environmental controls on gully initiation and development: flow hydraulics (critical flow shear stress), topography (i.e. slope gradient-contributing area thresholds), soil/ lithologic characteristics, land use (and its change) and weather/ climate conditions.

At Wet Swine Gill the exact date of rill/ main gully initiation is not known precisely; however, it can be firstly bracketed between 1 February 2002 (hillslope failure timing) and 17 June 2002 (first fixed point photo with observation of these erosional features). Rainfall records from Iron Crag (Figure 1 B and Figure 8) and site visit records enable the initiation timing to be more accurately estimated. Figure 8 shows rainfall conditions, during the time frame of interest. Excluding the failure date of 1 February 2002, this period includes ten rain days where rainfall depths exceed 20 mm, and three exceeding 40 mm when runoff from the upper hillslope and along the drainage channel would have been discharged directly on to the bare slide scar. However, a site visit on 23 May 2002, showed no clear slide scar dissection and a fine mineral sediment cover which was largely intact. This observation increases the likelihood of the rainfall on rain day 24 May 2002 (41.7 mm, max. intensity 3.6 mm h^{-1}) being responsible for rill initiation. This is broadly consistent with the suggestion of Poesen et al. (2003) that < 25 mm rain (per event or per day) is a threshold for rill initiation in European croplands. Topographic conditions are also favorable for rill initiation at Wet Swine Gill, comprising a steep scar surface (c. 35° (0.7 m m^{-1}) at the scar base where rilling began), and a large upslope contributing catchment area (0.31 km^2). When compared to published slope-area thresholds (i.e. Achten et al., 2008; Menéndez-Duarte et al., 2007; Nachtergaele et al., 2002; Parkner et al., 2006; Vandaele et al., 1996; Vandekerckhove et al., 1998, 2000) these values significantly exceed the minimum topographic thresholds required to initiate incision. In addition, scar surface ground conditions were bare with uneven/ uncompacted fine sediment covers, which Kirkby and Bracken (2009) consider ideal for the initiation of rill incision. These analyses suggest that the combination of topographic setting, ground conditions and rainfall timing/ severity contributed to the early onset of channelised flows (becoming the main gully) on the Wet Swine Gill slide scar.

7.2 Gully evolution: post initiation development

The recognition that gully size and shape develop over time is the basis of several conceptual gully evolution models (e.g. Betts et al., 2003; Harvey, 1992; Ireland et al., 1939; Kirkby and Bracken, 2009; Nachtergaele et al., 2002; Sidorchuk, 2006). These, in general, propose a common characteristic sequence comprising initial water incision of an un-gullied surface; followed by vertical downcutting, headward recession and the production of steep gully walls. Thereafter, in association with mass wasting, gully width increases and gully wall angles decline. Eventually re-vegetation and/ or gully bed aggradation, by both mass wasting and fluvial processes, may result in gully stabilisation.

However, the wider applicability of this self-stabilisation model has been questioned. Bocco (1991) suggests that it implies an over reliance on fluvial processes, and it assumes the re-establishment of vegetation. Whereas Parkner et al. (2006) suggest these models are not always suitable, as they describe a simple uni-directional development with no intervening periods of inactivity before final stabilisation. For example, in the context of gullying in the Waiapu basin, in New Zealand, between 1939 and 2003, they detail multiple phases of gully expansion (up to 18 years) and inactivity (up to 14 years), reflecting the episodic occurrence of major storms and shifting topographic thresholds in association with land use changes. Burkard and Kostaschuk (1997) also suggest that growth may continue; they provide the example of gullies adjoining the Lake Huron shoreline (Canada), where larger gullies have continued to grow by capturing smaller adjacent gullies. The medium-term monitoring data at Wet Swine Gill (Figures 3 & 4 and Tables 1 & 2) provide evidence in support of both the characteristic evolutionary model, but also periodic main gully growth via the capture of smaller adjacent gullies (Figures 3 & 4).

A further characteristic of gully evolution concerns the distribution of geomorphic work through time. Common trends have included linear change over multi-event/ annual/ long timescales (Oostwoud Wijdenes and Bryan, 2001; Saxton et al., 2012), and non-linear change over longer periods, with a very intense initial growth phase (Gang et al., 2009; Kirkby and Bracken, 2009; Sidorchuk, 1999, 2006; Vanwalleghem et al., 2005a, 2005b; Whitford et al., 2010). It has been suggested this non-linear pattern closely resembles a negative-exponential growth model. For example, Graf (1977) and Rutherford et al. (1997) apply this model to gully length change, at sites in Colorado and Australia, respectively. Nachtergaele et al. (2002) and Vanwalleghem et al. (2005a, 2005b) extend application to the Belgium loess belt, and explore not just gully length, but also declining expansion of planform gully surface area and volume, in relation to both time since gully formation, percentage gully life time and more directly cumulative rainfall and runoff. Testing of the applicability of this model for gully growth is performed using the medium-term cross sectional data from Wet Swine Gill.

Figure 9, shows the fit of non-linear regression functions to the field data. An exponential curve of the form $y=a(1\text{-}exp^{-bx})$, demonstrates a condition approximating negative exponential growth in main gully cross sectional width, depth and area relative to time since debris slide failure. At Wet Swine Gill all regression relations are strong and significant (R^2= 0.71 to 0.97 and P= <0.05 in all cases). The weakest relationship occurs for the base cross section depth change (Figure 9), where phases of gully infill and scour have occurred (Table 1).

Several hydrological and geomorphological explanations for this type of gully growth model have been suggested. Graf (1977) suggests growth is limited due to a decline in runoff area as gullies extend headwards; Rutherford et al. (1997) suggest a change from overland flow to seepage processes over time; whereas Nachtergaele et al. (2002) demonstrate that a decline in slope $\times$ area product (proportional to stream power) offers a better erosion-based explanation. At Wet Swine Gill the notable reduction in main gully growth c. 2-3 years following debris slide failure (Figure 9, Table 1) is coincident with the deliberate infilling of the drainage channel (Figure 1 D). This management strategy reduced the runoff catchment area above the slide scar from c. 0.31 km^2 to c. 0.02 km^2. Hence an explanation consistent with those suggested by Graf (1977) and Nachtergaele et al. (2002) may partly account for reduced erosion rates.

These analyses demonstrate that the application of a simple negative exponential growth model at Wet Swine Gill provides three useful insights. Firstly, it provides support to the hypothesis that runoff area reduction can reduce gully erosion rates; albeit through managed intervention. Secondly, this model is best suited to characterising the net erosional growth of gullies, and not their subsequent evolution by substantial net depositional processes. Thirdly, cross sectional data and associated width and depth measurements can be used to detect consistent patterns in gully development.

7.3 The relative significance of gully wall and bed processes

A number of investigations have suggested that gully sediment yield is dominated by gully wall sediment supply (Krause et al., 2003 [90-98%]; Martínez-Casasnovas et al., 2009 [>50%]; Thomas et al., 2009 [70%]). At Wet Swine Gill, Figure 5 (A) shows both net gully wall erosion and net gully bed deposition in the main gully between cross sections 5-10. However, these gully wall erosion rates (x) and gully bed deposition rates (y) are not proportional at-a-section (relationship y= -0.8125x + 0.0815, R^2= 0.05, P= 0.68), suggesting more complex sediment supply, storage and transfer behaviours for the consequent gully bed yield. They also only characterise one phase in the gully evolution model and rely on two dimensional cross section data expressed as net rates rather than sediment yields. Hence, determining the relative significance of the gully wall and gully bed is not straightforward; indeed larger magnitudes of bed deposition (Figures 5 A & 6 A) suggest periods of active bed sediment transfer (Johnson et al., 2010). It follows that more detailed investigation of gully wall and bed process-response relations in terms of both rates and yields are required to better address this question (Thomas et al., 2009).

7.4 Process activity greater in channelised (gully) rather than slope (scar) locations

At Wet Swine Gill, gully erosion, whilst localised, is far more active than non-channelised erosion of the adjacent slide scar despite its larger area. This is demonstrated in terms of both specific process rates (m^2 m^{-1} d^{-1}, i.e. space and time weighted for comparability) and sediment yield (kg dry mass). In particular, this study finds gully erosion process rates were up to 764% greater than that occurring on the slide scar (maximum values= gully wall: -0.0084; slide scar: -0.0011 m^2 m^{-1} d^{-1}; Figure 7); whilst Johnson et al. (2010) report that in the period June 2003 to January 2004 98% (1285 of 1316 kg) of net scar sediment transfer downslope was supplied by the gully. This differential activity reflects sediment storage on the slide scar (Johnson et al., 2010), and the dominant routing of surface runoff from the upper catchment (c. 0.31 km^2 prior to July 2004), along the main gully axis, thereby substantially reducing runoff to adjacent scar areas. This is important as concentrated (deeper and narrower) flows enable the generation of critical flow shear stresses and thus sediment entrainment and transport (Poesen et al., 2003). Furthermore, once a gully starts to form, additional processes (as observed at Wet Swine Gill) contribute to gully enlargement by positive feedback, i.e. headward recession (Oostwoud Wijdenes and Bryan, 2001; Wells et al., 2009), gully wall mass wasting (Kirkby and Bracken, 2009; Thomas et al., 2009) and adjacent gully capture (Burkard and Kostaschuk, 1997). Importantly this collection of active erosion processes does not take place on the scar surface.

The finding that gully erosion dominates sediment delivery at Wet Swine Gill, is not unique and has been previously reported elsewhere (e.g. Poesen et al., 2003; Tebebu et al., 2010; Vandekerckhove et al., 1998). However, Poesen et al. (2003) do note that the contribution of gully erosion to overall sediment production varies considerably, ranging 10 to 94%. They suggest the combination of the scale of the investigation (spatial and temporal) and environmental factors controlling gully erosion account for this variation.

7.5 Influence of rainfall upon sediment dynamics

Rainfall characteristics have been widely used in attempts to explain rill/ gully initiation and subsequent headward retreat (Oostwoud Wijdenes and Bryan, 2001; Poesen et al., 2003; Prosser and Soufi, 1998); gully and headwater stream sediment yields (Betts et al., 2003; Harvey, 1974; Johnson and Warburton, 2006); and the post failure sediment flux from landslide scars (Johnson et al., 2010; Larsen et al., 1999). This investigation at Wet Swine Gill has so far suggested that rainfall amount may be significant in the timing of scar rill/ gully initiation (c. 24 May 2002, Figure 8), and that subsequent episodes of enhanced drainage channel/ gully and slide scar erosion correspond with periods of increased wetness (Figure 7 & Table 3). In order to explore the significance of the relationship between sediment system activity (i.e. erosion or deposition, expressed as a time series of changing mean m^2 m^{-1} d^{-1}, as in Figure 7) and recorded meteorological conditions (derivatives of rainfall [mm] and ground surface temperature [°C], as in Table 3) linear regression analysis is used. Table 4 shows rainfall provides the highest levels of explanation for five out of the six geomorphic components (i.e. all except the right side of the scar). However, it is important not to over-interpret these data, as only 3 of 42 relationships are statistically significant ($P< 0.05$); these are between the main gully bed (depositional overall) and maximum 1 h rainfall ($P= 0.049$, $R^2= 0.31$), the main gully wall (erosional overall) and mean wet daily rainfall (P= 0.02, R^2= 0.39) and drainage channel bed (depositional overall) and mean wet daily rainfall (P= 0.02, R^2= 0.43). This suggests that rainfall generated channelised flows can influence gully bed and wall sediment production, although the strength of these relationships remain very weak (R^2 0.31- 0.43). These findings about relationship strength between channelised sediment dynamics and rainfall are in common with that reported by Johnson and Warburton (2006) at Iron Crag (R^2= 0.35- 0.38) and by Johnson et al. (2010) for this site (R^2= 0.31). The explanations offered by these studies are reinforced by this investigation. These being firstly, headwater sediment dynamics are highly episodic (Figure 7 A & B) and not effectively modeled by simple linear regression. Secondly, in order to increase understanding of process- response linkages it is necessary to improve the temporal resolution of sediment monitoring as it is substantially less than attained by the meteorological data series. Furthermore, Oostwoud Wijdenes and Bryan (2001) suggest that rainfall relations can be poor as rainfall does not always directly impact the erosional location, but instead leads to the generation of runoff over a wider area. Hence variations in the effective rainfall (i.e. runoff) will clearly impact the strength of subsequent unadjusted rainfall based relationships.

8.0 A MODEL OF SLIDE SCAR EVOLUTION

Figure 10 is a conceptual model for the post-failure development of a slide scar. This is based upon the Wet Swine Gill case study data between 2002 and 2014.

This model recognises five main phases, comprising: (1) post-failure scar exposure; (2) onset of rilling/ gullying; (3) rapid gully growth; (4) changing and slowing gully growth; and (5) slowing gully change and scar re-vegetation. These phases outline key process activity, landform features and management interventions; each expressed with an indication of their relative longevity (being the time since slide failure [TSSF]) and the relative proportion and direction (clockwise= increasing to measured maximum; anti-clockwise= decreasing from measured maximum) of cross sectional change (here based on main gully top cross section dimensions at the end of each phase, except phase 5 which uses 2013 data [last measurement]). As established previously, these phases at Wet Swine Gill broadly conform to existing conceptual gully evolution models (i.e. Betts et al., 2003; Burkard and Kostaschuk, 1997; Harvey, 1992; Ireland et al., 1939; Kirkby and Bracken, 2009; Nachtergaele et al., 2002; Sidorchuk, 2006; Whitford et al., 2010). Indeed this history of scar development provides further support for the changing post-failure sediment budget at this site, as outlined by Johnson et al. (2010). Specifically, gully erosion of landslide scars increases hillslope sediment supply so that hillslope sources eventually dominate over stream channel sources in accounting for the majority of headwater sediment flux.

It is apparent that both sediment budget models (e.g. Johnson et al., 2010) and conceptual geomorphic evolution models (here) of post-failure geomorphic activity increase understanding of headwater sediment dynamics. These can assist in the selection of management strategies and the subsequent evaluation of their effectiveness. However, the key test for any conceptual model (Figure 10) is its transferability in predicting landscape change beyond the original location and timescale from which it is derived. It follows that headwater sediment dynamics, and in particular the behaviour and significance of exposed landslide scars would benefit from further investigation across a range of environmental settings.

9.0 CONCLUSION

This paper has examined the development of a hillslope debris slide scar in the twelve years following its formation (1 February 2002), in the headwaters of Wet Swine Gill, in the English Lake District, UK. Results reveal four key observations: (1) gully evolution displayed distinct behaviours in respect to both change through time and adjustment in form (cross sectional area, depth and width); (2) gully walls were dominated by erosion and the gully bed by temporary deposition; (3) specific process rates were greater within channelised locations and less on the adjoining scar surface; and (4) erosional/ depositional process rates were partly controlled by rainfall, scar contributing runoff area and slope gradient. However, further detailed investigation is required as the relationships between meteorological factors and geomorphic activity were shown to be tentative and weak/ insignificant in the context of rainfall conditions.

Of particular interest were the gully evolution trajectories which showed initiation and rapid initial growth by vertical downcutting, followed by slowing rates of change dominated by width expansion and gully wall angle decline. This sequence was shown to exhibit strong and statistically significant conformity to a negative exponential growth model (Figure 9). These characteristics are summarised in a conceptual model of landslide scar evolution, which integrates existing conceptual descriptions of gully growth and capture (Figure 10). The transferability of this revised model requires further testing, based upon quantification of post-failure slide scar and gully dynamics in environments contrasting those existing in the UK uplands, and over varying timescales. Nevertheless, it follows, that continuing to develop scientific understanding of post-failure sediment supply from headwater hillslopes and channels, like Wet Swine Gill, will beneficially impact society; by helping to improve hazard and risk awareness for ecological and economic assets, to better underpin environmental management policy and help to identify management priorities, timescales and approaches. For example, in this particular case, it is apparent from the non-linear scar evolution, that earlier management intervention (i.e. between the initial event and the first few years coincident with rapid gully change) in reducing the runoff catchment area and re-vegetation of the bare slide scar would have very likely reduced the scale of post-failure hillslope sediment erosion.

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FIGURE AND TABLE CAPTIONS

Figure 1 The location of the Wet Swine Gill hillslope failure. (A) Northern Lake District in Northern England, (B) Upper River Caldew Catchment, (C) Oblique aerial view of the Wet Swine Gill catchment looking east to west (Photograph April 2005), (D) Infilling of the drainage channel near the hillslope failure (Photograph July 2004), (E) Hillslope failures on Blease Fell (Photograph, July 2012).

Figure 2 Slide scar monitoring network, incorporating medium- term and short-term cross sections and fixed point photography location (Survey date: 19 August 2003).

Figure 3 Repeat photographs of the debris slide scar area (monumented from FPP 1, Figure 2) showing morphological developments between July 2002 and July 2013.

Figure 4 Scar surface evolution measured at the medium-term cross sections at the top and base of the scar slope (August 2002 to July 2013).

Figure 5 Spatial variations in sediment dynamics (at-a-section [Figure 2], for the entire June 2003 to January 2004 period). (A) Drainage channel and main gully cross sections, (B) Scar cross sections.

Figure 6 Temporal variations in sediment dynamics (according to geomorphic component, at successive time points [monitoring intervals] within the June 2003 to January 2004 period). (A) Drainage channel and main gully cross sections, (B) Scar cross sections.

Figure 7 Specific sediment dynamics (according to geomorphic component, at successive time points [monitoring intervals] within the June 2003 to January 2004 period). (A) Drainage channel and main gully cross sections, (B) Scar cross sections.

Figure 8 Daily rainfall at Iron Crag (1 January 2002- 30 June 2002).

Figure 9 Main gully morphometric evolution as a function of time since debris slide failure, at medium-term cross section locations (February 2002 to July 2013).

Figure 10 Conceptual model of post-failure slide scar and gully development based upon the Wet Swine Gill case study.

Table 1 Main gully size & shape 2002-2013 (A) Measured dimensions, (B) Percentage change between selected surveys/ attributes.

Table 2 New left gullies sizes & shapes 2008-2013 (A) Measured dimensions, (B) Percentage change between surveys/ attributes.

Table 3 Recorded rainfall and ground surface temperature data for monitoring intervals during the period 27 June 2003 to 5 January 2004.

Table 4 Linear regression relationships between rainfall or temperature (*x*) and specific process rates (erosional and depositional mean m^2 m^{-1} d^{-1}) (*y*) across geomorphic components during the period 27 June 2003 to 5 January 2004.

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Table 1

A

Survey at Unequal Intervals	Top Cross Section- Main Gully				Base Cross Section- Main Gully			
	Max. Top Width (m)	Max. Depth (m)	Width/ Depth Ratio	Total Area (m^2)	Max. Top Width (m)	Max. Depth (m)	Width/ Depth Ratio	Total Area (m^2)
2002 (12/8/02)*	2.79~	0.16#	17.8~#	0.21~	2.10~	0.40#	5.2~#	0.68~
2003 (13/6/03)	2.00	1.47	1.4	1.84	2.20	0.90	2.4	1.39
2004 (26/3/04)	4.50	1.64	2.8	3.84	3.50	0.88	4.0	2.21
2008 (4/3/08)	4.59	1.34	3.4	3.71	-	-	-	-
2009 (30/11/09)	5.04	1.63	3.1	4.80	-	-	-	-
2010 (17/4/10)	5.14	1.53	3.3	4.79	5.20	0.51	10.2	1.44
2012 (12/7/12)	5.35	1.46	3.7	4.53	5.60	0.54	10.4	1.73
2013 (7/7/13)	5.34	1.42	3.8	4.23	5.65	0.62	9.1	1.81

* Data refer to multiple rills prior to the formation of the main gully in the same overall location

~ Values are the sum of all rill maximum widths and total areas, respectively at each cross section location. Multiple rills subsequently developed into a single larger gully at this locality

\# Mean depth of all rills at each cross section location

B

Survey Comparison	Top Cross Section- Main Gully			Base Cross Section- Main Gully		
	Width (% Δ)	Depth (% Δ)	Area (% Δ)	Width (% Δ)	Depth (% Δ)	Area (% Δ)
2002- 2003	-28	834	797	5	124	105
2003- 2004	125	12	109	59	-2	59
2004- 2008	2	-18	-3	-	-	-
2008- 2009	10	21	30	-	-	-
2009- 2010	2	-6	0	-	-	-
2004- 2010	-	-	-	49	-42	-35
2010- 2012	4	-5	-6	8	6	20
2012- 2013	0	-2	-6	1	15	5

(**Percentage change in survey comparisons** [Δ]: positive value= increase, negative value= decrease. This value is calculated as: the difference between the denominator [second measured value] and the numerator [first measured value], divided by numerator, and then multiplied by 100. First and second measured values are between successive surveys at each cross section location.)

Table 2

A

Survey at Unequal Intervals	Top Cross Section- Left 1 (L1)				Top Cross Section- Left 2 (L2)				L1 & L2
	Max. Top Width (m)	Max. Depth (m)	Width/ Depth Ratio	Area (m^2)	Max. Top Width (m)	Max. Depth (m)	Width/ Depth Ratio	Area (m^2)	Total Area (m^2)
2008 (4/3/08)	1.15	0.47	2.4	0.26	1.35	0.45	3.0	0.39	0.65
2009 (30/11/09)	1.25	0.58	2.1	0.29	1.65	0.59	2.8	0.64	0.93
2010 (17/4/10)	1.35	0.49	2.7	0.30	2.30	0.65	3.5	0.84	1.14
2012 (12/7/12)	1.40	0.37	3.8	0.19	2.40	0.65	3.7	0.87	1.06
2013 (7/7/13)	1.40	0.28	5.0	0.17	2.50	0.58	4.3	0.87	1.04

B

Survey Comparison	Top Cross Section- L1		Top Cross Section- L2		L1 & L2
	Width (% Δ)	Depth (% Δ)	Width (% Δ)	Depth (% Δ)	Total Area (% Δ)
2008- 2009	9	23	22	30	43
2009- 2010	8	-15	39	10	22
2010- 2012	4	-24	4	1	-7
2012- 2013	0	-26	4	-12	-2

(**Percentage change in survey comparisons** [Δ]: positive value= increase, negative value= decrease. This value is calculated as: the difference between the denominator [second measured value] and the numerator [first measured value], divided by numerator, and then multiplied by 100. First and second measured values are between successive surveys at each cross section location.)

Table 3

Monitoring Interval End Date	Meteorological Data						
	Max. 1 h Rain (mm) *	Mean 1 h Rain (mm) *	Mean Daily Rain (mm) **	Mean Wet Daily Rain (mm) ***	Min. Temp. (°C)	Mean Temp. (°C)	Max. Temp. (°C)
11/07/03	3.8	1.1	3.8	6.4	8.2	12.3	17.9
25/07/03	4.8	0.9	5.2	7.9	9.4	14.2	21.0
08/08/03	9.1	1.5	5.5	7.7	10.2	13.9	20.6
22/08/03	6.4	1.7	3.0	8.4	12.2	15.2	22.1
05/09/03	0.8	0.3	0.4	0.8	9.0	12.5	18.3
19/09/03	4.8	1.0	2.7	5.4	8.6	12.1	17.1
01/10/03	6.4	1.3	6.3	8.9	6.6	9.8	13.3
19/10/03	3.8	0.9	3.4	7.6	3.3	7.6	12.9
29/10/03	1.8	0.5	1.9	2.8	1.2	4.1	7.4
12/11/03	3.6	1.0	3.7	4.9	2.9	5.6	9.0
30/11/03	3.0	1.0	8.5	9.2	2.0	4.9	9.0
10/12/03	1.8	0.6	1.9	2.4	-0.2	3.4	6.2
05/01/04	6.4	1.4	7.8	13.4	-1.5	2.2	6.2

* 1 h values derived from hours in which rainfall is recorded (i.e. wet hours only)
** Mean Daily Rain- being the total rainfall depth divided by the total number of days comprising each monitoring interval
*** Mean Wet Daily Rain- the average 24 hr rainfall depth from those days in which rainfall is recorded (days= full calendar day relative to GMT; where occurring rainfall recorded during the 12h periods defining start and end days of a monitoring interval are excluded)

Table 4

Geomorphic Component	Dependent Data Sources (Time Series of Specific Process Rates) (see Figure 2 for locations)	Relationships of Independent Variable (Rainfall or Temperature Time Series) and Specific Process Rates: R^2 & (P value (significant if < 0.05))						
		Max. 1 h Rain	**Mean 1 h Rain**	**Mean Daily Rain**	**Mean Wet Daily Rain**	**Min. Temp.**	**Mean Temp.**	**Max. Temp.**
Drainage Channel- Wall	XS 1-4~	0.05 (0.47)	0.04 (0.53)	0.03 (0.54)	0.09 (0.32)	<0.01 (0.86)	<0.01 (0.81)	0.01 (0.79)
Drainage Channel- Bed	XS 1-4~	0.02 (0.62)	0.15 (0.20)	0.21 (0.11)	0.43 (0.02)	0.25 (0.08)	0.23 (0.10)	0.18 (0.14)
Main Gully- Wall	XS 5-15~	0.19 (0.14)	0.17 (0.16)	0.30 (0.055)	0.39 (0.02)	0.21 (0.12)	0.20 (0.13)	0.16 (0.17)
Main Gully- Bed	XS 5-15~	0.31 (0.049)	0.30 (0.053)	0.06 (0.42)	0.15 (0.19)	<0.01 (0.89)	<0.01 (0.90)	0.01 (0.81)
Scar- Right of Main Gully	XS 16-19~	0.03 (0.60)	<0.01 (0.94)	<0.01 (1.00)	0.03 (0.56)	0.26 (0.07)	0.28 (0.06)	0.24 (0.09)
Scar- Left of Main Gully	XS 20-24~	0.11 (0.27)	0.04 (0.49)	0.24 (0.09)	0.11 (0.28)	0.06 (0.44)	0.07 (0.37)	0.11 (0.27)

~ Full range of data sources (when available in a given monitoring interval)

Figure 1

Fig 1

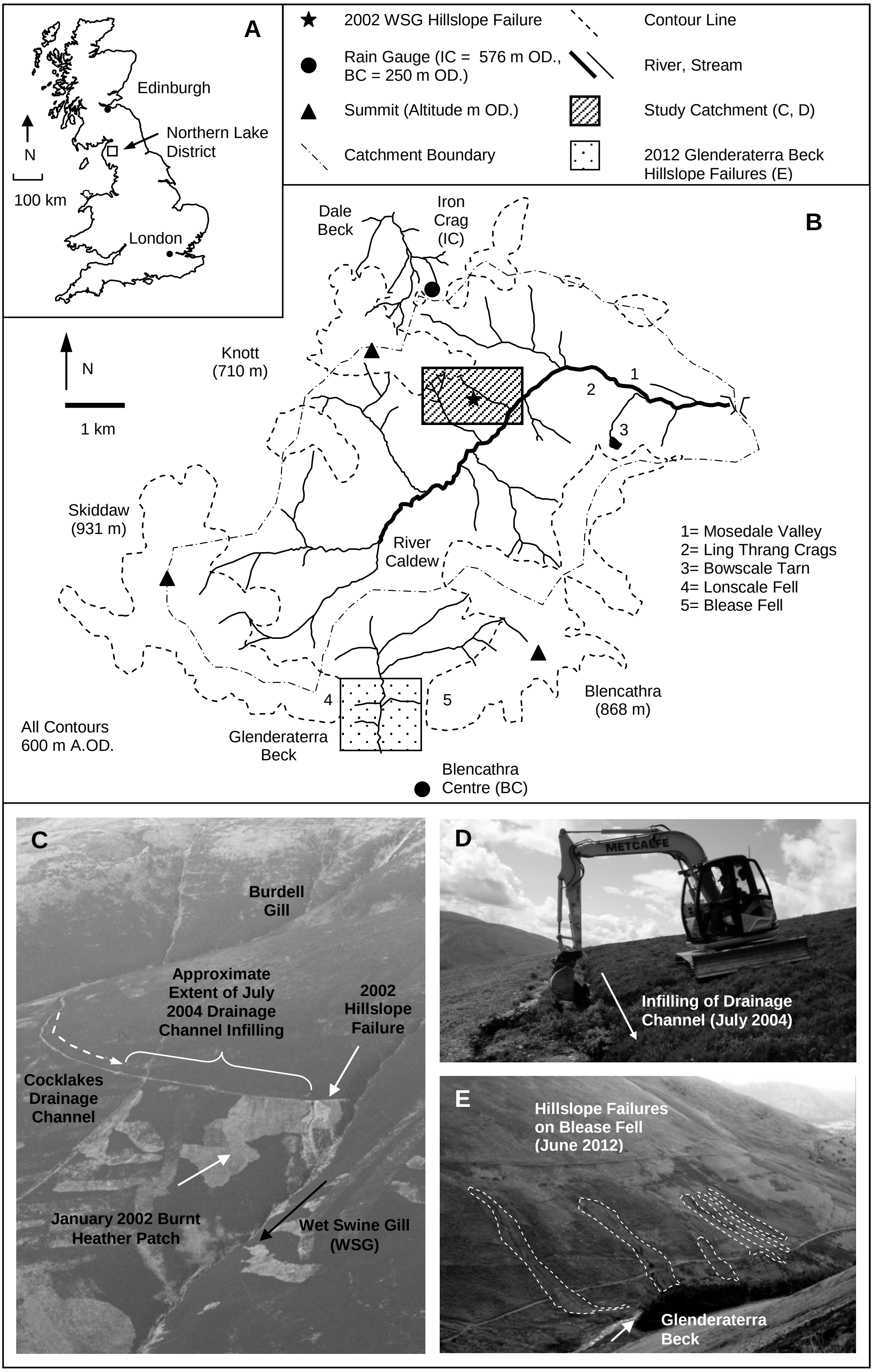


Figure 2

Fig 2

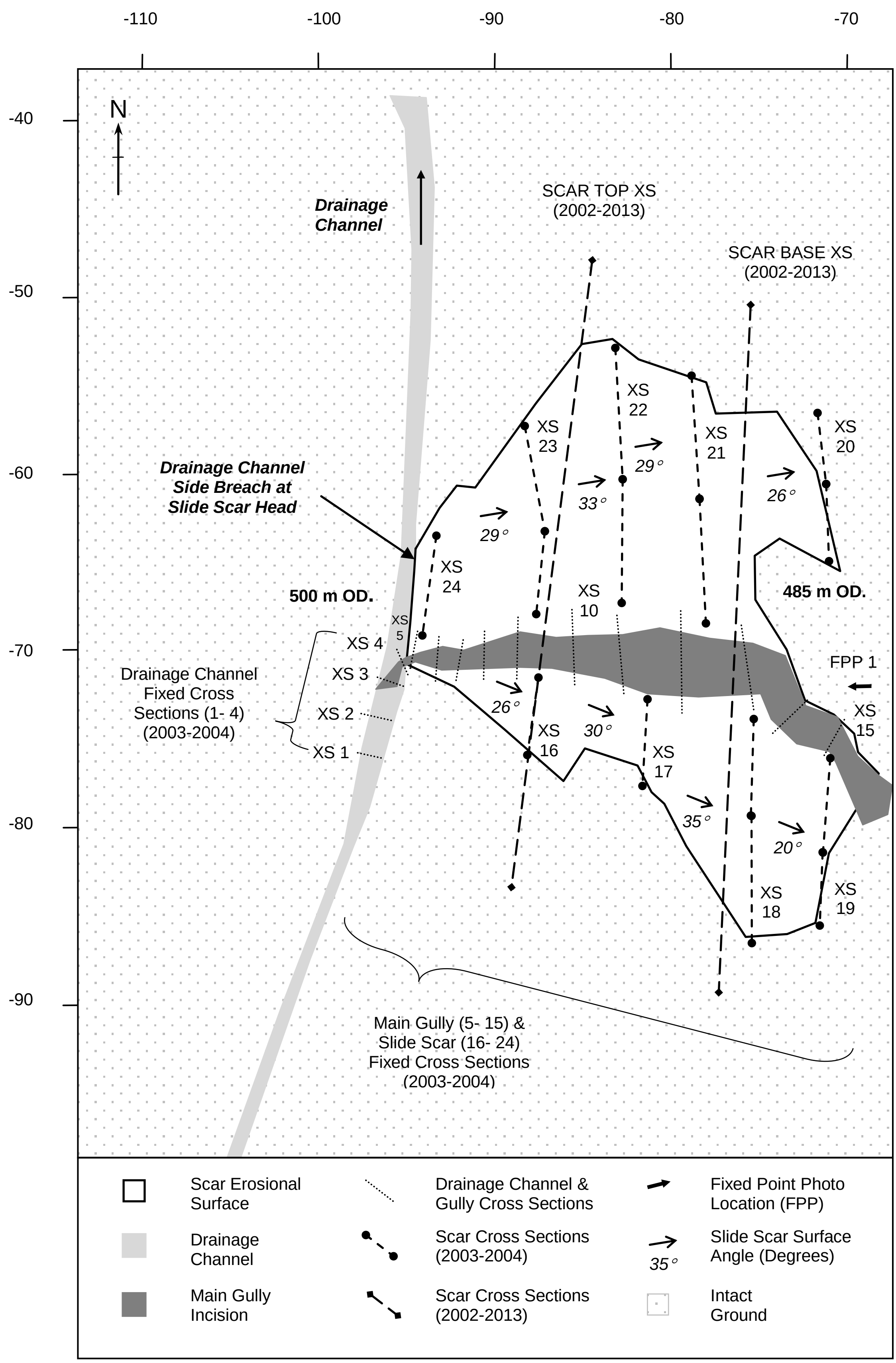


Figure 3 R1

Fig 3

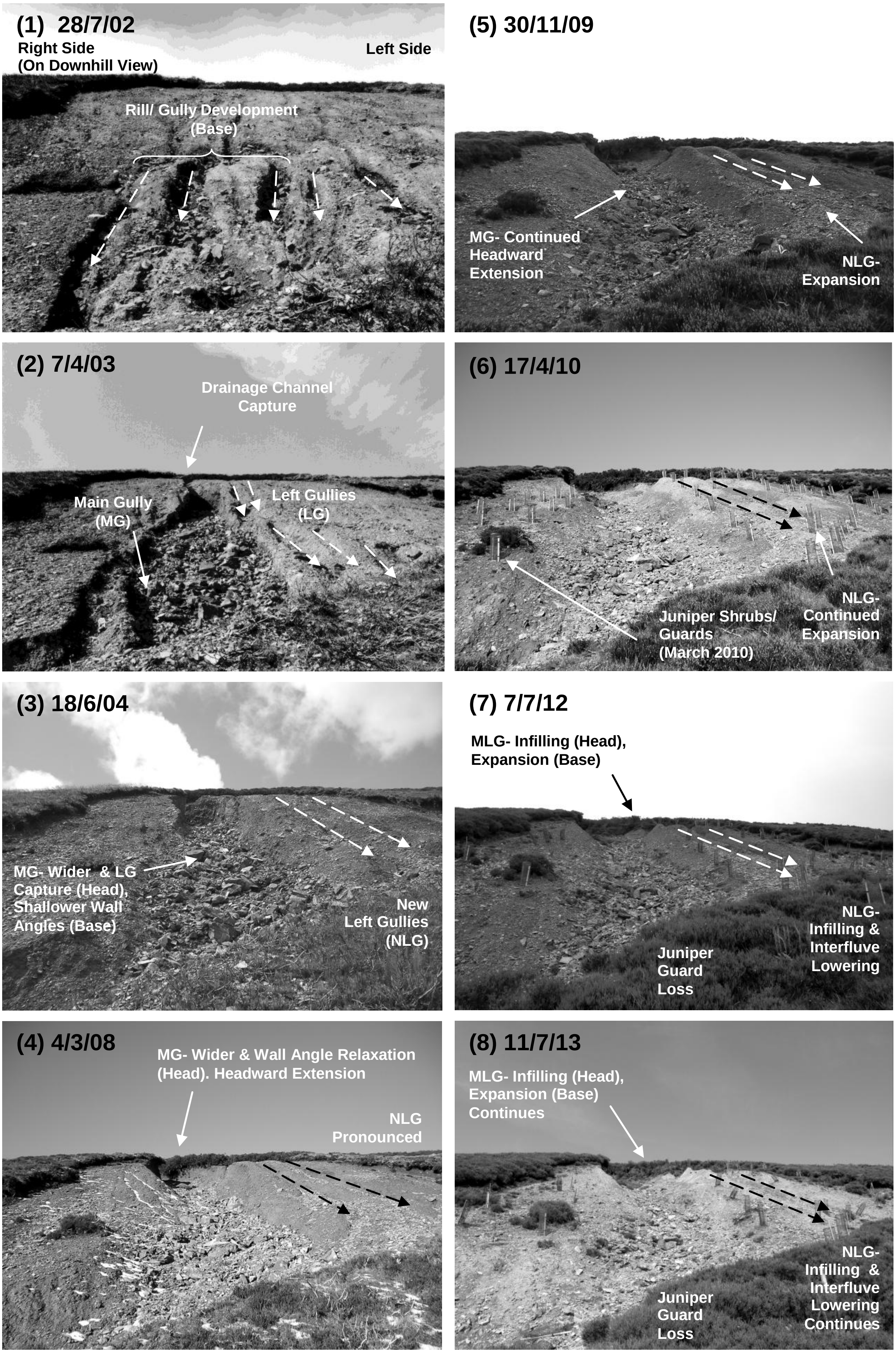


Figure 4 R1

Fig 4

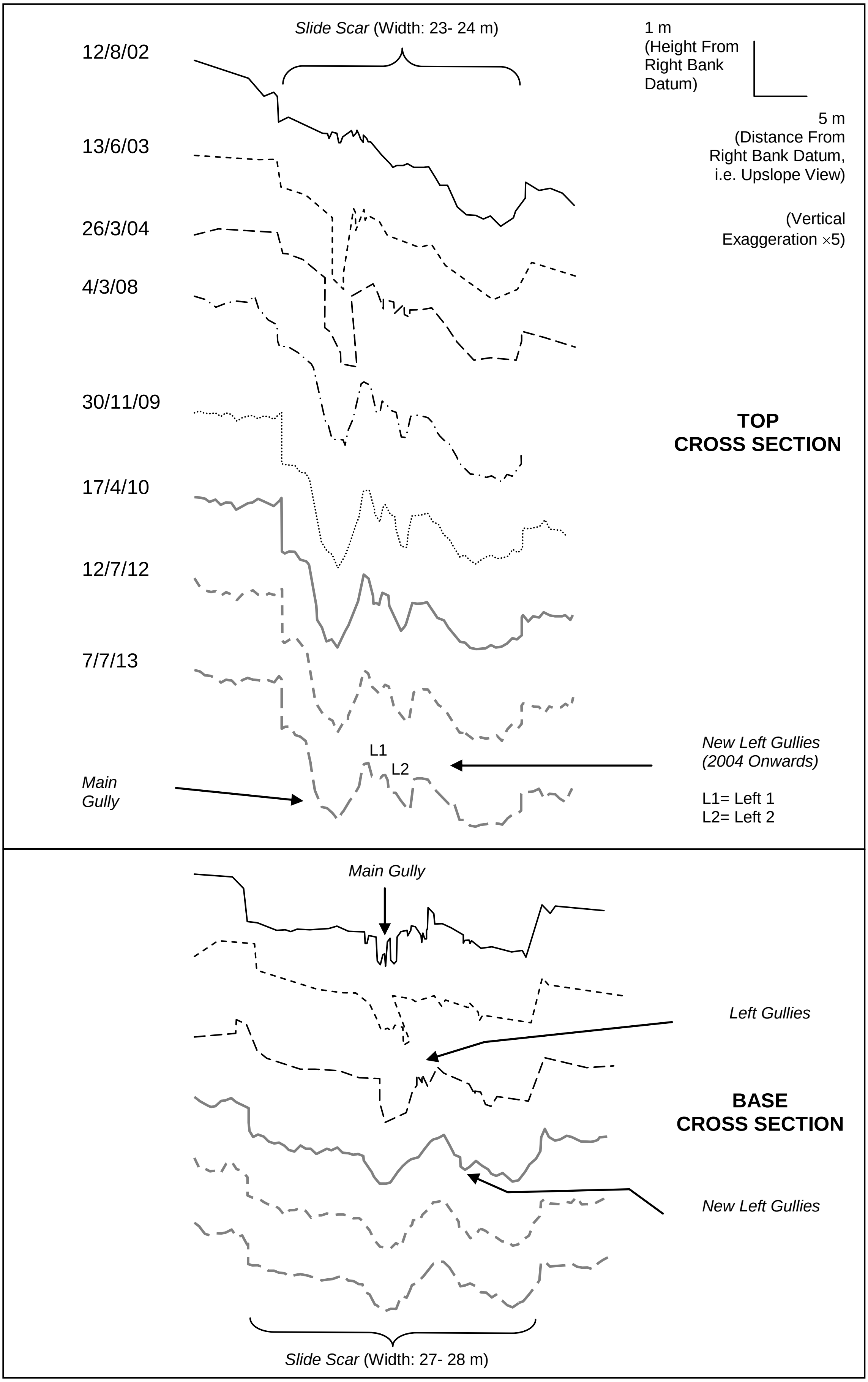


Figure 5

Fig 5

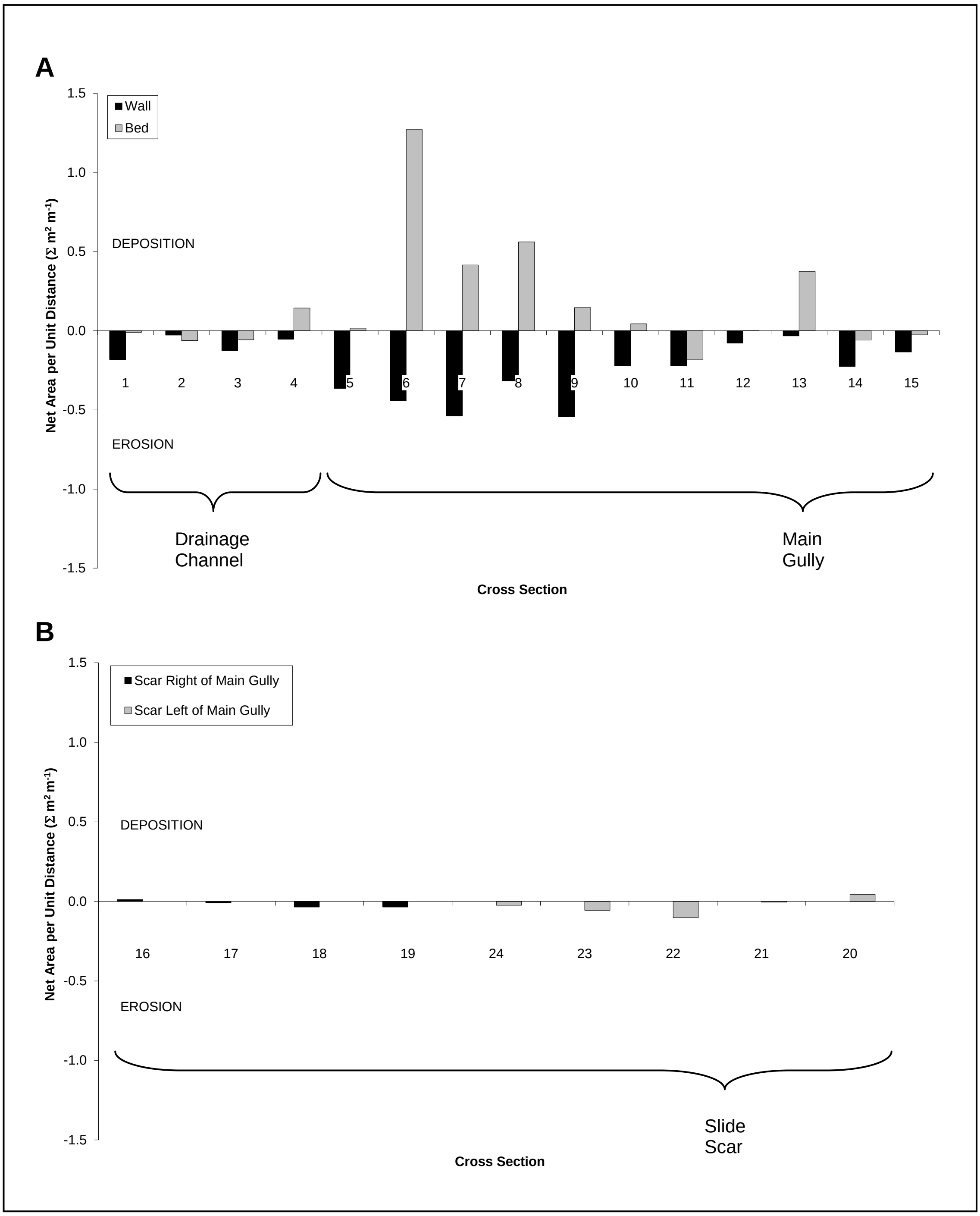


Figure 6

Fig 6

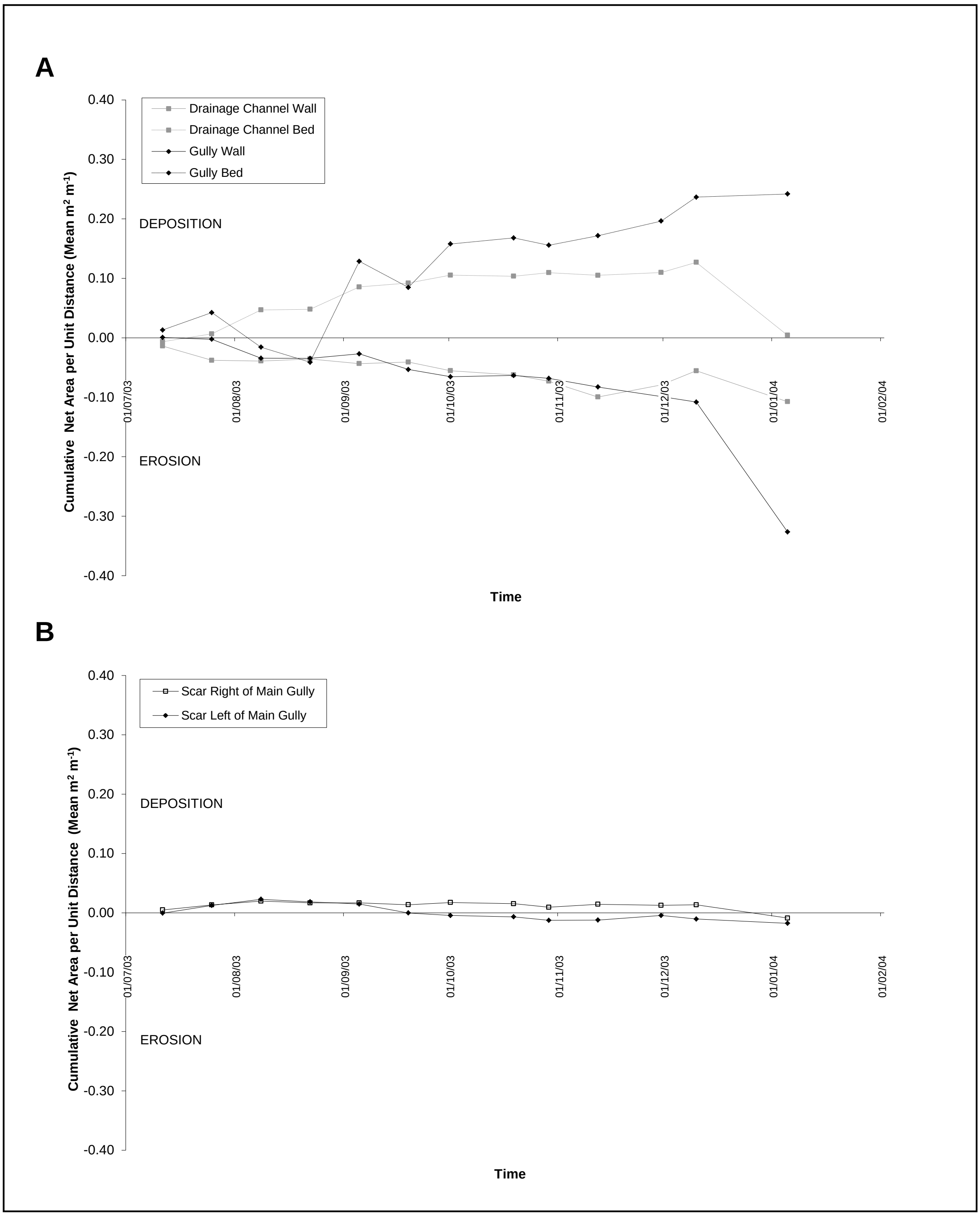


Figure 7

Fig 7

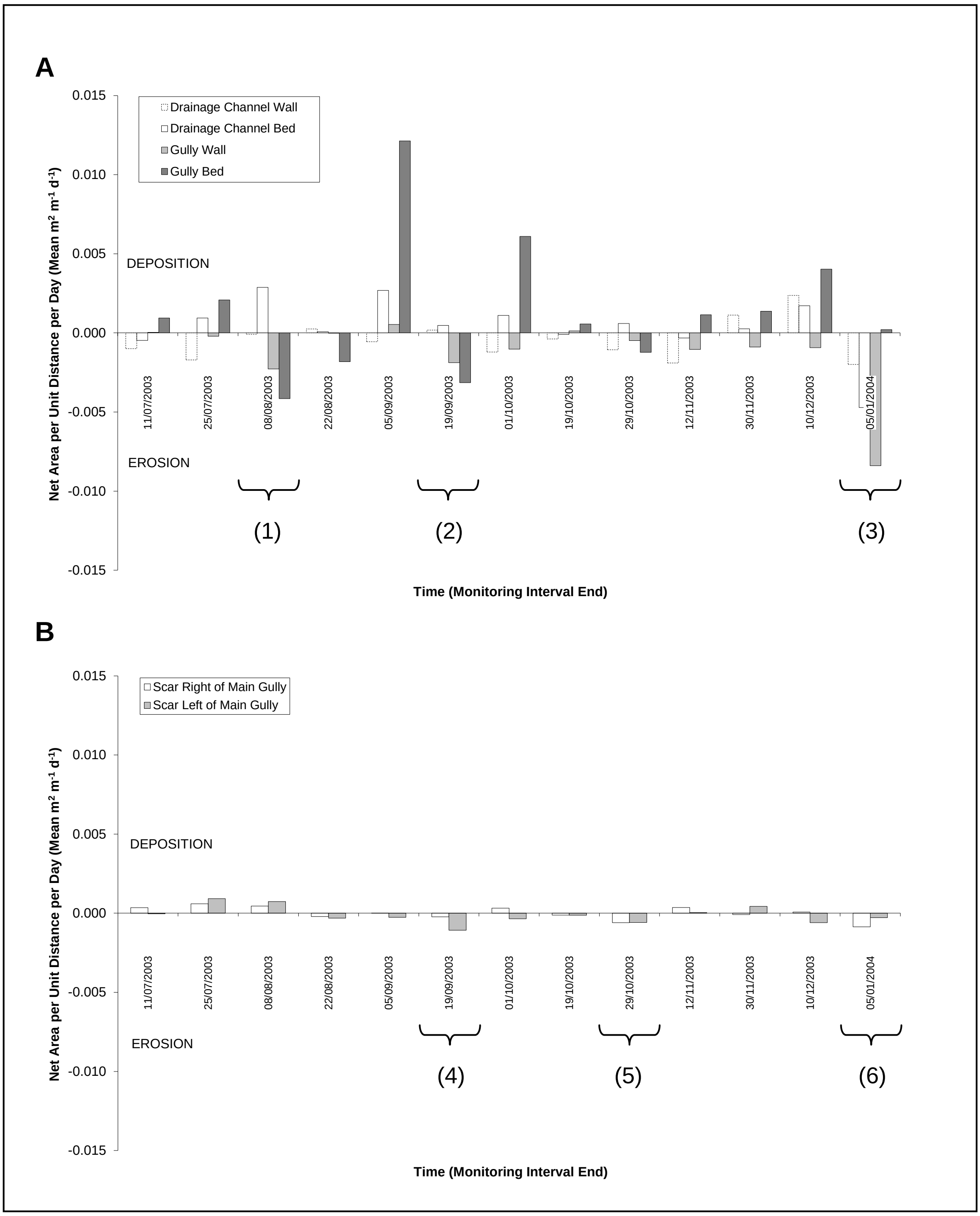


Figure 8

Fig 8

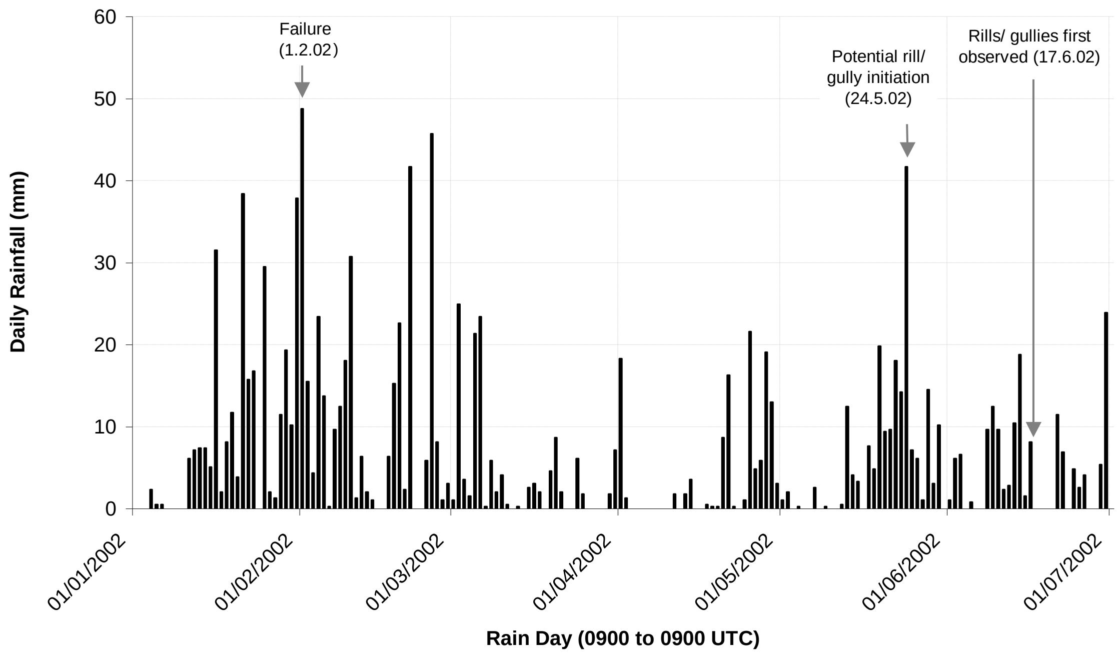


Figure 9

Fig 9

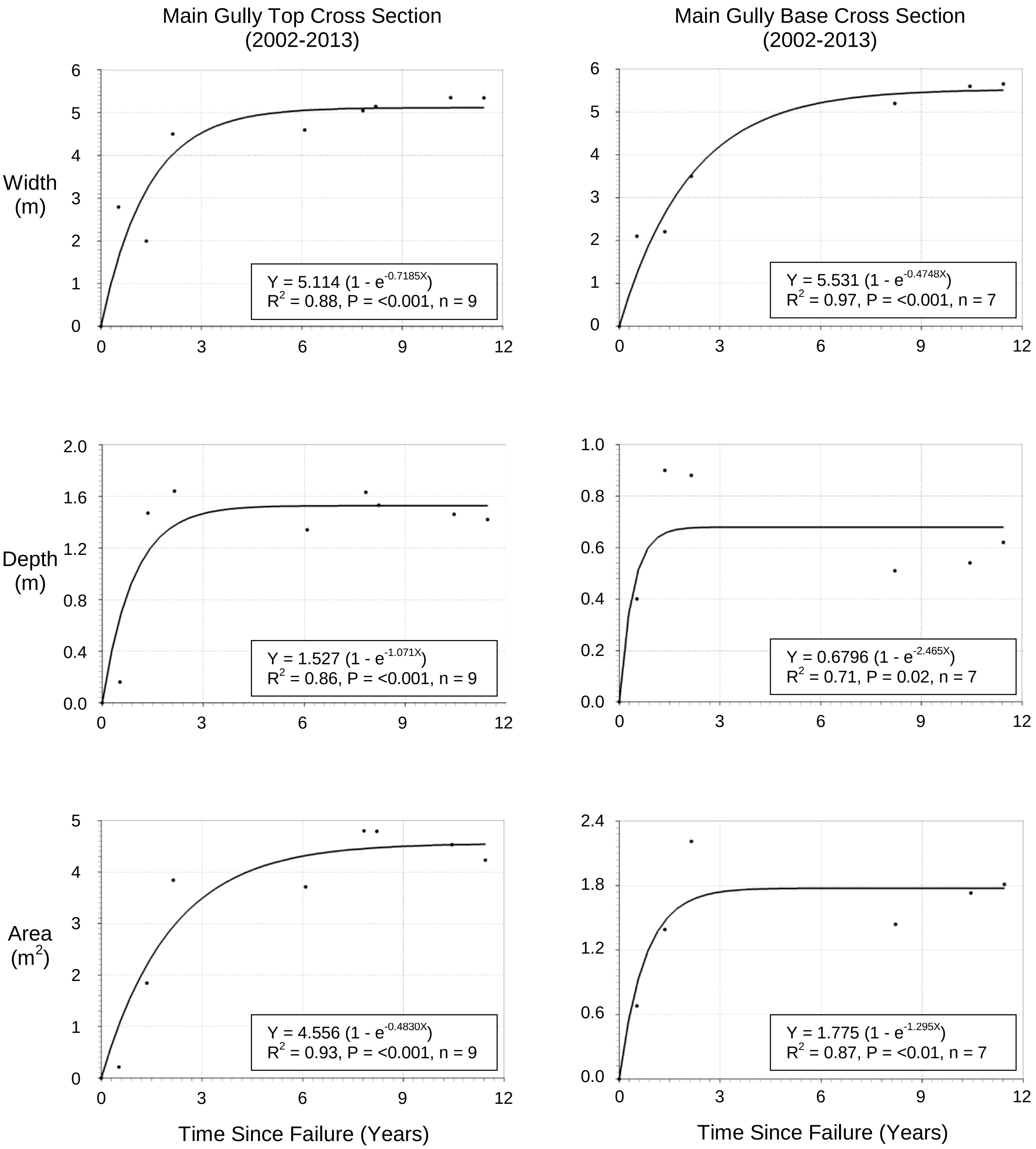
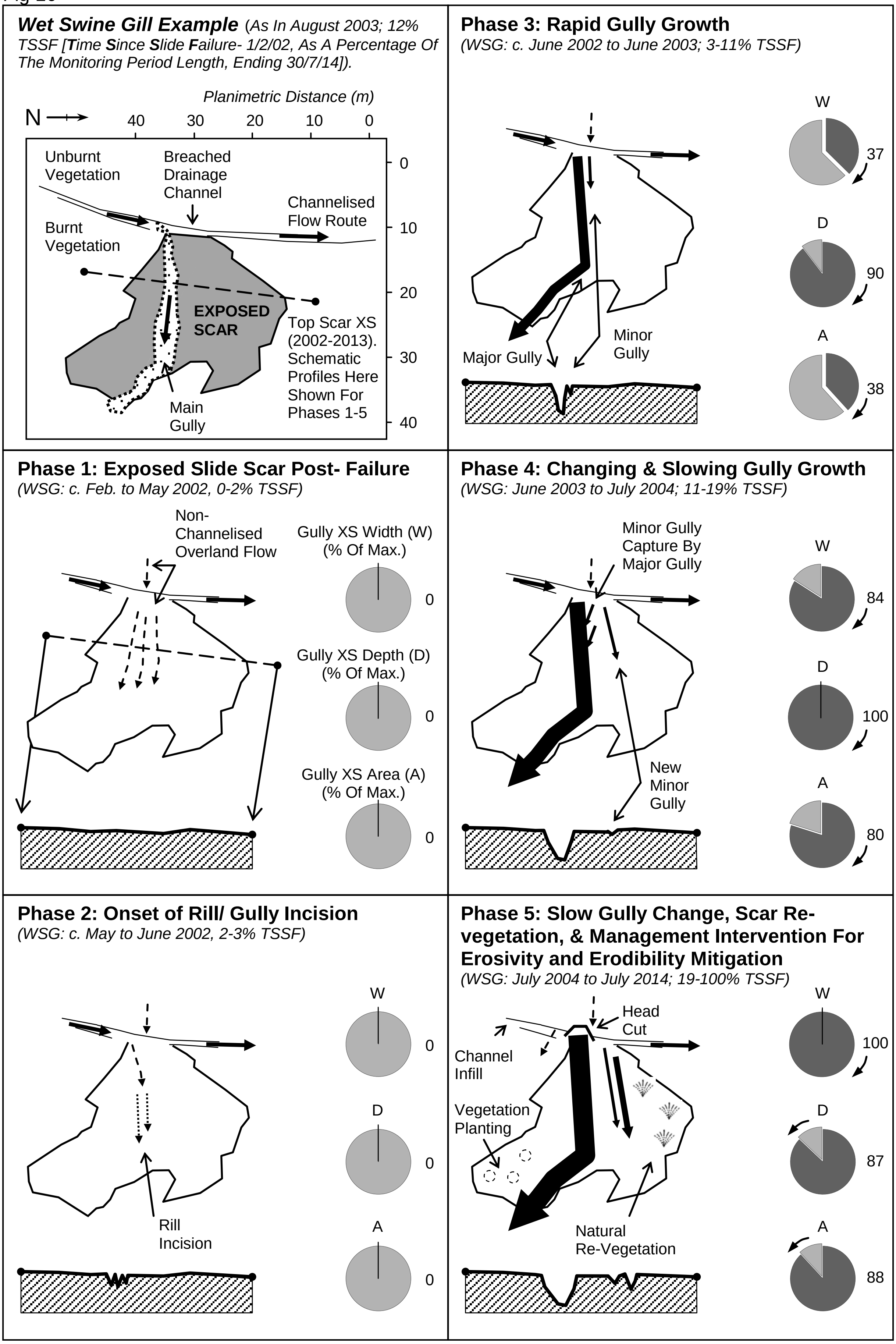


Figure 10

Fig 10



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

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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 remain 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.

KEY WORDS: headwater catchment; debris slide; medium-term sediment dynamics; erosion; gully development; meteorological conditions.

1.0 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 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., 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 program 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.

2.0 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 (Figure 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.) (Figure 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 Figure 1 B), and Clark and Wilson (2001) suggest debris ridges below Ling Thrang Crags (‘2’ on Figure 1 B) to be a terminal moraine from a Loch Lomond Stadial (LLS, c. 11-10 ka BP) glacier. Whilst Bowscale Tarn ('3' on Figure 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) (Figure 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) (Figure 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 (Figure 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.

3.0 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 (Figure 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 500-485 m OD., on a steep slope (0.58 m m^{-1} or 30 degrees); 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 (Figure 1 B & E); some transferred sediment and vegetation debris to Glenderaterra Beck. These slope failures coincide with a rainfall event on 22-23 June 2012 (Barron, 2012, personal communication; Met. Office, 2013), for which 93.8 mm was recorded at the Blencathra Centre (1.5 km SE of Glenderaterra Beck, Figure 1 B) (Keswick Reminder, 2012). These frequently recurring instances of hillslope failure continue to pose questions about the significance of hillslope sediment supply and transfer to sensitive downstream rivers and lakes (*cf.* Warburton, 2010) and are of considerable concern for local land management agencies.

4.0 POST- FAILURE SEDIMENT MONITORING PROGRAMME

Johnson et al. (2010) outline adjustment of the failed hillslope and adjacent Wet Swine Gill stream channel during the period 2002-2008. Using a multiple sediment budget approach (2002 [failure], 27 June 2003- 5 January 2004 and April 2008) where they examine the changing nature of failure and post-failure sediment dynamics. The key finding was a switching in the main source of sediment delivery from hillslope sources at the time of the failure (2002), followed by reworking of deposited channel sediments (2003-2004) and then (2008) a return to hillslope sediment supply.

In the present study, we examine in detail slide scar development and gullying using new data, which provide a longer, novel perspective on hillslope adjustment, and greater spatial resolution for the critical period 2003-2004 when erosion was amongst the most active. Data consist of: repeat photography from a fixed ground marker (2002-2014) (FPP 1 in Figure 2); repeat measurement of 'medium-term' monumented cross sections across the entire scar (2002-2013) (Figure 2); repeat measurement of 30 smaller 'short-term' monumented cross sections distributed across the drainage channel (*n*= 4), main gully (*n*= 11), and slide scar (*n*= 15) (June 2003- January 2004) (Figure 2). The impact of ground surface temperature fluctuations (at Wet Swine Gill) and rainfall variability (at Iron Crag) on sediment dynamics are analysed.

5.0 MEDIUM-TERM SLIDE SCAR DEVELOPMENT (2002-2014)

5.1 Ground-based photography & field observations

Twenty-one repeat photographs provide a qualitative record of hillslope development between 17 June 2002 and 30 July 2014 (12.12 years), with intervals ranging between 15 and 812 days (Figure 3 shows key images). Incision began soon after the exposure of the scar area; being well established by 17 June 2002. Initial development involved the formation of multiple (n= 6), linear and parallel rills/ gullies. Between August 2002 and April 2003 significant expansion of the rill network occurred, creating one main gully. The headward erosion of the main gully captured the drainage channel, thereby re-directing all the flow from drainage channel to Wet Swine Gill via the slide scar (Figure 1 C). The morphology of the main gully remained relatively stable until at least January 2004, although by June 2004 significant widening at the gully head and a reduction of the gully wall angles towards the base of the eroded hillslope were observed. Following deliberate permanent blocking of the drainage channel at the head of the slope (18-21 July 2004), gully development slowed with only minor widening and a small reduction of gully wall angles. By March 2008 (and thereafter) continued headward recession in the vicinity of the drainage channel, resulted in undermining of the former drainage channel bed and undercutting of the adjacent hillslope as shown by the overhanging vegetation.

Post-failure activity beyond the main gully was initially less marked, but became more prominent by 2008. The ‘left gullies’ (Figure 3) can be grouped into two sets, firstly shallow forms which existed prior to June 2004 and were captured by the widening of the main gully and; secondly, two gullies which developed nearer the scar edge (‘new left gullies’ in Figure 3), fed by runoff from the upper hillslope. By March 2008 these gullies transferred sediment beyond the scar perimeter, with coarse sediment eventually coupling with Wet Swine Gill (first observed in July 2012). Furthermore, ongoing interfluve lowering between them (Figures 3 and 4), may in time result in the capture of gully L1 by gully L2. These may also eventually merge with the main gully, triggering a new phase of activity.

Natural re-vegetation of the scar surface has been slow and localised. Heather (*Calluna vulgaris)* regrowth is most prominent on areas of degraded organic soil blocks; which are remnants of the former burnt peat surface not exported from the scar at the time of failure. These observations are consistent with previous observations which demonstrate that following fire heather will regenerate from basal stems and surviving seedbanks (e.g. Backshall et al., 2001; Gilchrist et al., 2003). In contrast, the exposed mineral soil surface is taking longer to recover, probably due to the loss of the overlying soil and pre-existing biological communities (e.g. Geertsema and Pojar, 2007; Gilchrist et al., 2003), combined with ongoing gully erosion which inhibits vegetation establishment (Imeson, 1971). However, observations from August 2009 identify the natural development of sparse/ juvenile grass and heather adjacent to the scar margin, i.e. the areas of greatest stability and closest proximity to existing seed banks. In response to this situation, Natural England and the Lake District National Park Authority (LDNPA) planted 150 Juniper shrubs (*Juniperus communis*) across both the scar (*n*= 120) and the surrounding pre-failure ground surface (*n*= 30) on 11- 12 March 2010 (Figure 3, photo 6). This experiment aims to promote slope stability and reduce sediment flux (Standring, 2010, personal communication). Figure 3 (photos 7 & 8) shows subsequent widespread loss/ tilting of the plastic nursery guards installed around the Juniper shrubs. By 30 July 2014, 39% of nursery guards had failed and only 30% of the planted shrubs were established. Furthermore, following February 2014, under a 2013 Higher Level Stewardship Agreement, the Caldbeck Commoners Association, LDNPA and Natural England, have planted 500 native trees on hillslopes adjacent to the Wet Swine Gill stream, with 64 immediately downslope of the scar (Barron, 2014, personal communication; Planning Inspectorate, 2014). Additional works are planned for later in 2014, including a temporary fence enclosure (consented for 15 years) around the failure scar (Barron, 2014, personal communication); this is part of a wider initiative in the Caldbeck Fells to reduce sediment transfer and improve water quality (Planning Inspectorate, 2014).

5.2 Cross section measurements (2002-2013)

Two monumented cross sections across the scar area (Figure 2) were resurveyed (n= ≤ 8 occasions) between 12 August 2002 and 7 July 2013 (Table 1 A and Table 2 A). Measurements were obtained using an automatic level and stadia staff (2003 & 2004); or inclined tape line, clinometer and measurement rule (2002 and 2008 onwards).

Figure 4 shows the evolution of the scar surface at the top and base of the slope. This demonstrates that scar width has remained relatively stable since the hillslope failure, with significant change being focused on the scar surface.

Table 1 and Figure 4 show the growth of the main gully (as also outlined in Figure 3). Based on these data, four key observations standout; firstly, between August 2002 and June 2003 a rapid transition of main gully size and shape occurred. Gully area percentage change (%Δ, as defined in Table 1) increases at the two cross sections, ranging 105% (0.68 to 1.39 m^2) to 797% (0.21 to 1.84 m^2). This enlargement is dominated by vertical incision (e.g. 0.16 to 1.47 m at top cross section) accompanied with minor lateral growth (e.g. 2.10 to 2.20 m at base cross section). As a consequence, width-depth ratios reduce markedly; for example, at the top cross section from 17.8 to 1.4. Secondly, between June 2003 and March 2004, change was much less rapid and lateral expansion of the main gully became more important than vertical incision; where gully-top width percentage changes for the top and base of scar cross sections are: 125% (2 to 4.5 m) and 59% (2.2 to 3.5 m) respectively, contrasting depth changes of 12% (1.47 to 1.64 m) and -2% (0.9 to 0.88 m) respectively. Thirdly, following 2004, changes at the top cross section slowed considerably. Here, gully width increased from 4.50 m in 2004 to 5.35 m in 2012, with percentage change between successive surveys being generally less than 10%; an accompanying trend towards sediment infilling is reflected in reducing depths (1.64 m in 2004 to 1.42 m in 2013) and reducing area following a peak size of 4.80 m^2 in 2009 to 4.23 m^2 in 2013. The gully shape in this period showed relative stability where width-depth ratios are low and evolving from around 3 to 4. Fourthly, the main gully in the base cross section in the period following 2004, has constantly increased in width but with diminishing magnitude of percentage change: 49% (2004-2010), 8% (2010-2012), 1% (2012-2013); an initial sediment infilling phase 2004-2010 of -35% (2.21 to 1.44 m^2) has since reversed indicated by depth and area increases, with percentage change between surveys not exceeding 15% and 20%, respectively. The gully width-depth ratio is variable, ranging from 4 to 10.4 since 2004, but becoming more stable following 2010, between 9 to 10.

Figure 4 and Table 2 also show the change in the two 'new left gullies'. They evolve in a similar pattern to the neighbouring main gully (top cross section). This includes four key observations. Firstly, in the period March 2008 to November 2009 the combined area of both gullies increased by 43% (0.65 to 0.93 m^2). A slightly greater proportion of this growth is accounted for by depth increase (23 to 30%) rather than width increase (9 to 22%). Secondly, from 2009 onwards growth in width is sustained, albeit with declining rates of growth (8 to 0 % at L1 and 39 to 4 % at L2). Thirdly, following initial increases in depth (up until 2009 for L1 and up until 2012 for L2), sediment infilling is particularly noticeable, up to a -26% reduction in depth (0.37 to 0.28 m) at L1 in the period 2012-2013. A corresponding reduction in the total area of both L1 and L2 occurs following 2010 (1.14 m^2 to 1.04 m^2). Fourthly, gully width-depth ratios, whilst similar to the main gully, are typically more dynamic in the short-term, here they range 2.1 to 5 for L1 and 2.8 to 4.3 for L2. This increased sensitivity may reflect the different scales of the gullies relative to grain size which comprises the sedimentary infill i.e. a single large boulder can have a large influence on form in the smaller gullies.

6.0 SHORT-TERM SLIDE SCAR DEVELOPMENT (2003-2004)

6.1 Monitoring method

The 30 short-term cross section (XS) profiles were measured on up to 14 occasions, at an interval of approximately 14 days (range: 10- 26 days), using an inclined tape (width) and measurement staff (depth). Measurement errors were minimised according to a rule set throughout the study period that included: keeping the tape taught, fixing the tape at a standard elevation on the end-point monuments, avoiding adverse weather (wind, snow covered ground), reading the depth on the top of the inclined tape and taking measurements at set intervals along the tape (0.1 m for XS 1-15 and 0.25 m for XS 16-24, Figure 2). A subsequent data validation exercise removed anomalous data, providing 346 profile comparisons (from a maximum of 390). These data determine the net change in cross sectional area (m^2) at a profile location, between two points in time (i.e. a monitoring interval, t_i to t_{ii} etc.), with change partitioned into drainage channel/ gully wall and bed elements for XS 1-15 (Figure 2). Where changes are either net erosional (sediment production > sediment storage) or net depositional (sediment production < sediment storage).

6.2 Drainage channel, main gully & scar surface cross sectional dynamics (June 2003- January 2004)

Detailed understanding of the spatial and temporal characteristics of sediment dynamics in these geomorphic components of the debris slide/ gully system are provided by standardised process rate data, which allow for the variations in cross section bed/ scar width or wall height (i.e. unit distance). Derivatives of net area per unit distance (m^2 m^{-1}) are used in Figures 5 and 6; where Figure 5 shows spatial variations over the entire 2003-2004 period and Figure 6 depicts cumulative behaviour over time (i.e. monitoring intervals comprising the 2003-2004 period). Further, Figure 7 shows specific process rates in m^2 m^{-1} d^{-1}.

Figure 5 shows the net area per unit distance change aggregated over the entire 2003-2004 period (Σ m^2 m^{-1}), with partitioning into geomorphic components (i.e. drainage channel, main gully, slide scar) and wall and bed elements for XS 1-15. In general, the main gully (XS 5-15) is most active, followed by the drainage channel (XS 1-4), with the least activity on the slide scar (XS 16-24). In Figure 5 (A) cross sections 5-10 all have gully wall erosion rates exceeding -0.2 m^2 m^{-1} (range: -0.22 to -0.54 m^2 m^{-1}) and gully bed deposition of variable and sometimes greater magnitude (range: 0.02 to 1.27 m^2 m^{-1}). This spatial extent of more active gully wall erosion and gully bed deposition (see Figure 2 for locations) corresponds with that previously described as experiencing headward erosion by April 2003 (Figure 3) and gully enlargement principally through width expansion between June 2003 and March 2004 (Figure 4 Top XS and Table 1). Above (XS 1-4) and below (XS 11-15) the area of active head cut, process rates are typically less (maxima: -0.23 m^2 m^{-1} [wall] and 0.38 m^2 m^{-1} [bed]), and dominantly erosional, probably reflecting reduced wall sediment supply. Figure 5 (B) shows lower process rates which are typically erosional (0.04 to -0.10 m^2 m^{-1}). In this area of the debris slide scar, there are slightly increasing erosion rates downslope (i.e. XS 17 to 19 and XS

24 to 22). This pattern is consistent with areas susceptible to erosion by overland flow, due to increasing scar slope angles prior to cross section locations (XS 17 & 18 [30° & 35°] & XS 23 & 22 [29° & 33°]), and increasing contributing flow area downslope (both are shown by Figure 2). Additionally, these patterns may also reflect differences in material properties, although there are currently insufficient data at this site to explore this hypothesis. Secondly, a depositional toe deposit occurs after XS 22, this corresponds with a local reduction in gradient (XS 24- 22: 0.63 m m^{-1} [32°], XS 21-20: 0.49 m m^{-1} [26°]). Thirdly, the differences in erosion rates on either side of the gully are slight, albeit the left side of the gully is more active (-0.03 to -0.10 m^2 m^{-1}) than the right side (-0.01 to -0.04 m^2 m^{-1}).

Figure 6 shows the cumulative change over time in net erosion and deposition in geomorphic components. These data are based upon an average (mean m^2 m^{-1}) from multiple cross section locations, as grouped in Figure 2. Figure 6 clearly shows the greatest change in the main gully and least change on the slide scar. The overall trends are net scar erosion, net wall erosion and net bed deposition. In particular, Figure 6 (A) shows the dominant cumulative behaviour for walls is erosional and beds depositional; where the latter are typically of greater magnitude. Secondly, the drainage channel and main gully walls have similar cumulative rates of erosion until 12 November 2003 (up to c. 0.1 m^2 m^{-1}), thereafter increasing gully wall erosion is particularly marked (up to 0.33 m^2 m^{-1}). Thirdly, drainage channel and gully bed behaviours are more divergent in terms of both the direction of cumulative change (i.e. phases of storage gain and depletion) and the relative magnitude between each. Figure 6 (B) clearly demonstrates lower process rates on the scar area, and a weak tendency to net erosion by the end of the study period.

Figure 7 shows the change in specific process rates over time (mean $m^2\ m^{-1}\ d^{-1}$) in geomorphic components. Figure 7 supports the overall trends shown in Figures 5 and 6, but also identifies three pronounced erosional phases in the main gully walls and frequently the bed (Figure 7(A)). These are monitoring intervals: (1) 25 July to 8 August 2003 (wall: -0.002 $m^2\ m^{-1}\ d^{-1}$; bed: -0.004 $m^2\ m^{-1}\ d^{-1}$), (2) 5 to 19 September 2003 (wall: -0.002 $m^2\ m^{-1}\ d^{-1}$; bed: -0.003 $m^2\ m^{-1}\ d^{-1}$) and (3) 10 December 2003 to 5 January 2004 (wall: -0.008 $m^2\ m^{-1}\ d^{-1}$). These time intervals coincide with episodes of increased wetness (Table 3), particularly shown by higher maximum 1-hour rainfall intensity (9.1, 4.8 and 6.4 mm h^{-1}, respectively). Johnson et al. (2010) also identify the same July to August 2003 and December 2003 to January 2004 intervals, in respect to significant increments in gully sediment yield. Figure 7 (B) shows slightly increased rates of erosion (up to -0.001 $m^2\ m^{-1}\ d^{-1}$) across the entire scar, on three occasions: (4) 5 to 19 September 2003, (5) 19 to 29 October 2003 and (6) 10 December 2003 to 5 January 2004. So there is reasonable similarity to the timing of pronounced erosional phases in the main gully.

7.0 DISCUSSION OF POST- FAILURE SLIDE SCAR DEVELOPMENT

The preceding sections detail the characteristics of slide scar/ gully change at Wet Swine Gill over 12 years. Findings can be summarised into four key observations. Firstly, gully evolution exhibits distinct behaviours in respect to both timescale and adjustment of form. Initially main gully growth is rapid, comprising coalescence of rills and headward extension, and thereafter rates of gully change typically slow over time. Gully change is initially dominated by vertical downcutting followed by greater width expansion and gully wall angle decline. Secondly, in respect to the main gully, walls tend to be erosional, and the bed dominantly depositional; with bed locations typically showing higher process rates than those occurring on the gully walls. Thirdly, highest rates of geomorphic change are associated with drainage channel/ gully features, rather than the spatially more extensive scar surface. Finally, variations in erosion/ deposition rates are influenced by rainfall, scar contributing runoff area and slope gradient.

7.1 Gully evolution: initiation

A number of studies suggest that gully initiation can occur soon after landscape disturbance. For example, Prosser and Soufi (1998) in reference to slopes near Bombala, New South Wales, Australia, identify gully initiation within one year of intensive forest clearance. Similarly, Warburton et al. (2003) in discussion of the February 1995 Hart Hope peat slide in the North Pennines, UK, identify fluvial gully development soon after the failure. Prosser and Soufi (1998) suggest that this early onset of gullying reflects an increased environmental susceptibility (i.e. high erodibility) following soil disturbance and degradation of vegetation covers. These exposed ground surfaces may then be subject to formative rainfall-runoff events (i.e. events of high erosivity) that exceed the surface erosional resistance. They suggest that in the Bombala case resistance to channel initiation recovers within a year of disturbance, through vegetation regrowth, soil compaction and increased infiltration; although where gullying has begun, this acts to inhibit recovery thereby maintaining susceptibility to erosion. It is therefore important to determine where and why gullying develops. In this respect, Poesen et al. (2003) and Valentin et al. (2005) consider the following to be the key environmental controls on gully initiation and development: flow hydraulics (critical flow shear stress), topography (i.e. slope gradient-contributing area thresholds), soil/ lithologic characteristics, land use (and its change) and weather/ climate conditions.

At Wet Swine Gill the exact date of rill/ main gully initiation is not known precisely; however, it can be firstly bracketed between 1 February 2002 (hillslope failure timing) and 17 June 2002 (first fixed point photo with observation of these erosional features). Rainfall records from Iron Crag (Figure 1 B and Figure 8) and site visit records enable the initiation timing to be more accurately estimated. Figure 8 shows rainfall conditions, during the time frame of interest. Excluding the failure date of 1 February 2002, this period includes ten rain days where rainfall depths exceed 20 mm, and three exceeding 40 mm when runoff from the upper hillslope and along the drainage channel would have been discharged directly on to the bare slide scar. However, a site visit on 23 May 2002, showed no clear slide scar dissection and a fine mineral sediment cover which was largely intact. This observation increases the likelihood of the rainfall on rain day 24 May 2002 (41.7 mm, max. intensity 3.6 mm h^{-1}) being responsible for rill initiation. This is broadly consistent with the suggestion of Poesen et al. (2003) that < 25 mm rain (per event or per day) is a threshold for rill initiation in European croplands. Topographic conditions are also favorable for rill initiation at Wet Swine Gill, comprising a steep scar surface (c. 35° (0.7 m m^{-1}) at the scar base where rilling began), and a large upslope contributing catchment area (0.31 km^2). When compared to published slope-area thresholds (i.e. Achten et al., 2008; Menéndez-Duarte et al., 2007; Nachtergaele et al., 2002; Parkner et al., 2006; Vandaele et al., 1996; Vandekerckhove et al., 1998, 2000) these values significantly exceed the minimum topographic thresholds required to initiate incision. In addition, scar surface ground conditions were bare with uneven/ uncompacted fine sediment covers, which Kirkby and Bracken (2009) consider ideal for the initiation of rill incision. These analyses suggest that the combination of topographic setting, ground conditions and rainfall timing/ severity contributed to the early onset of channelised flows (becoming the main gully) on the Wet Swine Gill slide scar.

7.2 Gully evolution: post initiation development

The recognition that gully size and shape develop over time is the basis of several conceptual gully evolution models (e.g. Betts et al., 2003; Harvey, 1992; Ireland et al., 1939; Kirkby and Bracken, 2009; Nachtergaele et al., 2002; Sidorchuk, 2006). These, in general, propose a common characteristic sequence comprising initial water incision of an un-gullied surface; followed by vertical downcutting, headward recession and the production of steep gully walls. Thereafter, in association with mass wasting, gully width increases and gully wall angles decline. Eventually re-vegetation and/ or gully bed aggradation, by both mass wasting and fluvial processes, may result in gully stabilisation.

However, the wider applicability of this self-stabilisation model has been questioned. Bocco (1991) suggests that it implies an over reliance on fluvial processes, and it assumes the re-establishment of vegetation. Whereas Parkner et al. (2006) suggest these models are not always suitable, as they describe a simple uni-directional development with no intervening periods of inactivity before final stabilisation. For example, in the context of gullying in the Waiapu basin, in New Zealand, between 1939 and 2003, they detail multiple phases of gully expansion (up to 18 years) and inactivity (up to 14 years), reflecting the episodic occurrence of major storms and shifting topographic thresholds in association with land use changes. Burkard and Kostaschuk (1997) also suggest that growth may continue; they provide the example of gullies adjoining the Lake Huron shoreline (Canada), where larger gullies have continued to grow by capturing smaller adjacent gullies. The medium-term monitoring data at Wet Swine Gill (Figures 3 & 4 and Tables 1 & 2) provide evidence in support of both the characteristic evolutionary model, but also periodic main gully growth via the capture of smaller adjacent gullies (Figures 3 & 4).

A further characteristic of gully evolution concerns the distribution of geomorphic work through time. Common trends have included linear change over multi-event/ annual/ long timescales (Oostwoud Wijdenes and Bryan, 2001; Saxton et al., 2012), and non-linear change over longer periods, with a very intense initial growth phase (Gang et al., 2009; Kirkby and Bracken, 2009; Sidorchuk, 1999, 2006; Vanwalleghem et al., 2005a, 2005b; Whitford et al., 2010). It has been suggested this non-linear pattern closely resembles a negative-exponential growth model. For example, Graf (1977) and Rutherford et al. (1997) apply this model to gully length change, at sites in Colorado and Australia, respectively. Nachtergaele et al. (2002) and Vanwalleghem et al. (2005a, 2005b) extend application to the Belgium loess belt, and explore not just gully length, but also declining expansion of planform gully surface area and volume, in relation to both time since gully formation, percentage gully life time and more directly cumulative rainfall and runoff. Testing of the applicability of this model for gully growth is performed using the medium-term cross sectional data from Wet Swine Gill.

Figure 9, shows the fit of non-linear regression functions to the field data. An exponential curve of the form $y=a(1-exp^{-bx})$, demonstrates a condition approximating negative exponential growth in main gully cross sectional width, depth and area relative to time since debris slide failure. At Wet Swine Gill all regression relations are strong and significant (R^2= 0.71 to 0.97 and P= <0.05 in all cases). The weakest relationship occurs for the base cross section depth change (Figure 9), where phases of gully infill and scour have occurred (Table 1).

Several hydrological and geomorphological explanations for this type of gully growth model have been suggested. Graf (1977) suggests growth is limited due to a decline in runoff area as gullies extend headwards; Rutherford et al. (1997) suggest a change from overland flow to seepage processes over time; whereas Nachtergaele et al. (2002) demonstrate that a decline in slope $\times$ area product (proportional to stream power) offers a better erosion-based explanation. At Wet Swine Gill the notable reduction in main gully growth c. 2-3 years following debris slide failure (Figure 9, Table 1) is coincident with the deliberate infilling of the drainage channel (Figure 1 D). This management strategy reduced the runoff catchment area above the slide scar from c. 0.31 km^2 to c. 0.02 km^2. Hence an explanation consistent with those suggested by Graf (1977) and Nachtergaele et al. (2002) may partly account for reduced erosion rates.

These analyses demonstrate that the application of a simple negative exponential growth model at Wet Swine Gill provides three useful insights. Firstly, it provides support to the hypothesis that runoff area reduction can reduce gully erosion rates; albeit through managed intervention. Secondly, this model is best suited to characterising the net erosional growth of gullies, and not their subsequent evolution by substantial net depositional processes. Thirdly, cross sectional data and associated width and depth measurements can be used to detect consistent patterns in gully development.

7.3 The relative significance of gully wall and bed processes

A number of investigations have suggested that gully sediment yield is dominated by gully wall sediment supply (Krause et al., 2003 [90-98%]; Martínez-Casasnovas et al., 2009 [>50%]; Thomas et al., 2009 [70%]). At Wet Swine Gill, Figure 5 (A) shows both net gully wall erosion and net gully bed deposition in the main gully between cross sections 5-10. However, these gully wall erosion rates (x) and gully bed deposition rates (y) are not proportional at-a-section (relationship y= -0.8125x + 0.0815, R^2= 0.05, P= 0.68), suggesting more complex sediment supply, storage and transfer behaviours for the consequent gully bed yield. They also only characterise one phase in the gully evolution model and rely on two dimensional cross section data expressed as net rates rather than sediment yields. Hence, determining the relative significance of the gully wall and gully bed is not straightforward; indeed larger magnitudes of bed deposition (Figures 5 A & 6 A) suggest periods of active bed sediment transfer (Johnson et al., 2010). It follows that more detailed investigation of gully wall and bed process-response relations in terms of both rates and yields are required to better address this question (Thomas et al., 2009).

7.4 Process activity greater in channelised (gully) rather than slope (scar) locations

At Wet Swine Gill, gully erosion, whilst localised, is far more active than non-channelised erosion of the adjacent slide scar despite its larger area. This is demonstrated in terms of both specific process rates (m^2 m^{-1} d^{-1}, i.e. space and time weighted for comparability) and sediment yield (kg dry mass). In particular, this study finds gully erosion process rates were up to 764% greater than that occurring on the slide scar (maximum values= gully wall: -0.0084; slide scar: -0.0011 m^2 m^{-1} d^{-1}; Figure 7); whilst Johnson et al. (2010) report that in the period June 2003 to January 2004 98% (1285 of 1316 kg) of net scar sediment transfer downslope was supplied by the gully. This differential activity reflects sediment storage on the slide scar (Johnson et al., 2010), and the dominant routing of surface runoff from the upper catchment (c. 0.31 km^2 prior to July 2004), along the main gully axis, thereby substantially reducing runoff to adjacent scar areas. This is important as concentrated (deeper and narrower) flows enable the generation of critical flow shear stresses and thus sediment entrainment and transport (Poesen et al., 2003). Furthermore, once a gully starts to form, additional processes (as observed at Wet Swine Gill) contribute to gully enlargement by positive feedback, i.e. headward recession (Oostwoud Wijdenes and Bryan, 2001; Wells et al., 2009), gully wall mass wasting (Kirkby and Bracken, 2009; Thomas et al., 2009) and adjacent gully capture (Burkard and Kostaschuk, 1997). Importantly this collection of active erosion processes does not take place on the scar surface.

The finding that gully erosion dominates sediment delivery at Wet Swine Gill, is not unique and has been previously reported elsewhere (e.g. Poesen et al., 2003; Tebebu et al., 2010; Vandekerckhove et al., 1998). However, Poesen et al. (2003) do note that the contribution of gully erosion to overall sediment production varies considerably, ranging 10 to 94%. They suggest the combination of the scale of the investigation (spatial and temporal) and environmental factors controlling gully erosion account for this variation.

7.5 Influence of rainfall upon sediment dynamics

Rainfall characteristics have been widely used in attempts to explain rill/ gully initiation and subsequent headward retreat (Oostwoud Wijdenes and Bryan, 2001; Poesen et al., 2003; Prosser and Soufi, 1998); gully and headwater stream sediment yields (Betts et al., 2003; Harvey, 1974; Johnson and Warburton, 2006); and the post failure sediment flux from landslide scars (Johnson et al., 2010; Larsen et al., 1999). This investigation at Wet Swine Gill has so far suggested that rainfall amount may be significant in the timing of scar rill/ gully initiation (c. 24 May 2002, Figure 8), and that subsequent episodes of enhanced drainage channel/ gully and slide scar erosion correspond with periods of increased wetness (Figure 7 & Table 3). In order to explore the significance of the relationship between sediment system activity (i.e. erosion or deposition, expressed as a time series of changing mean m^2 m^{-1} d^{-1}, as in Figure 7) and recorded meteorological conditions (derivatives of rainfall [mm] and ground surface temperature [°C], as in Table 3) linear regression analysis is used. Table 4 shows rainfall provides the highest levels of explanation for five out of the six geomorphic components (i.e. all except the right side of the scar). However, it is important not to over-interpret these data, as only 3 of 42 relationships are statistically significant ($P< 0.05$); these are between the main gully bed (depositional overall) and maximum 1 h rainfall ($P= 0.049$, $R^2= 0.31$), the main gully wall (erosional overall) and mean wet daily rainfall (P= 0.02, R^2= 0.39) and drainage channel bed (depositional overall) and mean wet daily rainfall (P= 0.02, R^2= 0.43). This suggests that rainfall generated channelised flows can influence gully bed and wall sediment production, although the strength of these relationships remain very weak (R^2 0.31- 0.43). These findings about relationship strength between channelised sediment dynamics and rainfall are in common with that reported by Johnson and Warburton (2006) at Iron Crag (R^2= 0.35- 0.38) and by Johnson et al. (2010) for this site (R^2= 0.31). The explanations offered by these studies are reinforced by this investigation. These being firstly, headwater sediment dynamics are highly episodic (Figure 7 A & B) and not effectively modeled by simple linear regression. Secondly, in order to increase understanding of process- response linkages it is necessary to improve the temporal resolution of sediment monitoring as it is substantially less than attained by the meteorological data series. Furthermore, Oostwoud Wijdenes and Bryan (2001) suggest that rainfall relations can be poor as rainfall does not always directly impact the erosional location, but instead leads to the generation of runoff over a wider area. Hence variations in the effective rainfall (i.e. runoff) will clearly impact the strength of subsequent unadjusted rainfall based relationships.

8.0 A MODEL OF SLIDE SCAR EVOLUTION

Figure 10 is a conceptual model for the post-failure development of a slide scar. This is based upon the Wet Swine Gill case study data between 2002 and 2014.

This model recognises five main phases, comprising: (1) post-failure scar exposure; (2) onset of rilling/ gullying; (3) rapid gully growth; (4) changing and slowing gully growth; and (5) slowing gully change and scar re-vegetation. These phases outline key process activity, landform features and management interventions; each expressed with an indication of their relative longevity (being the time since slide failure [TSSF]) and the relative proportion and direction (clockwise= increasing to measured maximum; anti-clockwise= decreasing from measured maximum) of cross sectional change (here based on main gully top cross section dimensions at the end of each phase, except phase 5 which uses 2013 data [last measurement]). As established previously, these phases at Wet Swine Gill broadly conform to existing conceptual gully evolution models (i.e. Betts et al., 2003; Burkard and Kostaschuk, 1997; Harvey, 1992; Ireland et al., 1939; Kirkby and Bracken, 2009; Nachtergaele et al., 2002; Sidorchuk, 2006; Whitford et al., 2010). Indeed this history of scar development provides further support for the changing post-failure sediment budget at this site, as outlined by Johnson et al. (2010). Specifically, gully erosion of landslide scars increases hillslope sediment supply so that hillslope sources eventually dominate over stream channel sources in accounting for the majority of headwater sediment flux.

It is apparent that both sediment budget models (e.g. Johnson et al., 2010) and conceptual geomorphic evolution models (here) of post-failure geomorphic activity increase understanding of headwater sediment dynamics. These can assist in the selection of management strategies and the subsequent evaluation of their effectiveness. However, the key test for any conceptual model (Figure 10) is its transferability in predicting landscape change beyond the original location and timescale from which it is derived. It follows that headwater sediment dynamics, and in particular the behaviour and significance of exposed landslide scars would benefit from further investigation across a range of environmental settings.

9.0 CONCLUSION

This paper has examined the development of a hillslope debris slide scar in the twelve years following its formation (1 February 2002), in the headwaters of Wet Swine Gill, in the English Lake District, UK. Results reveal four key observations: (1) gully evolution displayed distinct behaviours in respect to both change through time and adjustment in form (cross sectional area, depth and width); (2) gully walls were dominated by erosion and the gully bed by temporary deposition; (3) specific process rates were greater within channelised locations and less on the adjoining scar surface; and (4) erosional/ depositional process rates were partly controlled by rainfall, scar contributing runoff area and slope gradient. However, further detailed investigation is required as the relationships between meteorological factors and geomorphic activity were shown to be tentative and weak/ insignificant in the context of rainfall conditions.

Of particular interest were the gully evolution trajectories which showed initiation and rapid initial growth by vertical downcutting, followed by slowing rates of change dominated by width expansion and gully wall angle decline. This sequence was shown to exhibit strong and statistically significant conformity to a negative exponential growth model (Figure 9). These characteristics are summarised in a conceptual model of landslide scar evolution, which integrates existing conceptual descriptions of gully growth and capture (Figure 10). The transferability of this revised model requires further testing, based upon quantification of post-failure slide scar and gully dynamics in environments contrasting those existing in the UK uplands, and over varying timescales. Nevertheless, it follows, that continuing to develop scientific understanding of post-failure sediment supply from headwater hillslopes and channels, like Wet Swine Gill, will beneficially impact society; by helping to improve hazard and risk awareness for ecological and economic assets, to better underpin environmental management policy and help to identify management priorities, timescales and approaches. For example, in this particular case, it is apparent from the non-linear scar evolution, that earlier management intervention (i.e. between the initial event and the first few years coincident with rapid gully change) in reducing the runoff catchment area and re-vegetation of the bare slide scar would have very likely reduced the scale of post-failure hillslope sediment erosion.

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FIGURE AND TABLE CAPTIONS

Figure 1 The location of the Wet Swine Gill hillslope failure. (A) Northern Lake District in Northern England, (B) Upper River Caldew Catchment, (C) Oblique aerial view of the Wet Swine Gill catchment looking east to west (Photograph April 2005), (D) Infilling of the drainage channel near the hillslope failure (Photograph July 2004), (E) Hillslope failures on Blease Fell (Photograph, July 2012).

Figure 2 Slide scar monitoring network, incorporating medium- term and short-term cross sections and fixed point photography location (Survey date: 19 August 2003).

Figure 3 Repeat photographs of the debris slide scar area (monumented from FPP 1, Figure 2) showing morphological developments between July 2002 and July 2013.

Figure 4 Scar surface evolution measured at the medium-term cross sections at the top and base of the scar slope (August 2002 to July 2013).

Figure 5 Spatial variations in sediment dynamics (at-a-section [Figure 2], for the entire June 2003 to January 2004 period). (A) Drainage channel and main gully cross sections, (B) Scar cross sections.

Figure 6 Temporal variations in sediment dynamics (according to geomorphic component, at successive time points [monitoring intervals] within the June 2003 to January 2004 period). (A) Drainage channel and main gully cross sections, (B) Scar cross sections.

Figure 7 Specific sediment dynamics (according to geomorphic component, at successive time points [monitoring intervals] within the June 2003 to January 2004 period). (A) Drainage channel and main gully cross sections, (B) Scar cross sections.

Figure 8 Daily rainfall at Iron Crag (1 January 2002- 30 June 2002).

Figure 9 Main gully morphometric evolution as a function of time since debris slide failure, at medium-term cross section locations (February 2002 to July 2013).

Figure 10 Conceptual model of post-failure slide scar and gully development based upon the Wet Swine Gill case study.

Table 1 Main gully size & shape 2002-2013 (A) Measured dimensions, (B) Percentage change between selected surveys/ attributes.

Table 2 New left gullies sizes & shapes 2008-2013 (A) Measured dimensions, (B) Percentage change between surveys/ attributes.

Table 3 Recorded rainfall and ground surface temperature data for monitoring intervals during the period 27 June 2003 to 5 January 2004.

Table 4 Linear regression relationships between rainfall or temperature (*x*) and specific process rates (erosional and depositional mean $m^2\ m^{-1}\ d^{-1}$) (*y*) across geomorphic components during the period 27 June 2003 to 5 January 2004.

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Table 1

A

Survey at Unequal Intervals	Top Cross Section- Main Gully				Base Cross Section- Main Gully			
	Max. Top Width (m)	Max. Depth (m)	Width/ Depth Ratio	Total Area (m^2)	Max. Top Width (m)	Max. Depth (m)	Width/ Depth Ratio	Total Area (m^2)
2002 (12/8/02)*	2.79~	0.16#	17.8~#	0.21~	2.10~	0.40#	5.2~#	0.68~
2003 (13/6/03)	2.00	1.47	1.4	1.84	2.20	0.90	2.4	1.39
2004 (26/3/04)	4.50	1.64	2.8	3.84	3.50	0.88	4.0	2.21
2008 (4/3/08)	4.59	1.34	3.4	3.71	-	-	-	-
2009 (30/11/09)	5.04	1.63	3.1	4.80	-	-	-	-
2010 (17/4/10)	5.14	1.53	3.3	4.79	5.20	0.51	10.2	1.44
2012 (12/7/12)	5.35	1.46	3.7	4.53	5.60	0.54	10.4	1.73
2013 (7/7/13)	5.34	1.42	3.8	4.23	5.65	0.62	9.1	1.81

* Data refer to multiple rills prior to the formation of the main gully in the same overall location

~ Values are the sum of all rill maximum widths and total areas, respectively at each cross section location. Multiple rills subsequently developed into a single larger gully at this locality

Mean depth of all rills at each cross section location

B

Survey Comparison	Top Cross Section- Main Gully			Base Cross Section- Main Gully		
	Width (% Δ)	Depth (% Δ)	Area (% Δ)	Width (% Δ)	Depth (% Δ)	Area (% Δ)
2002- 2003	-28	834	797	5	124	105
2003- 2004	125	12	109	59	-2	59
2004- 2008	2	-18	-3	-	-	-
2008- 2009	10	21	30	-	-	-
2009- 2010	2	-6	0	-	-	-
2004- 2010	-	-	-	49	-42	-35
2010- 2012	4	-5	-6	8	6	20
2012- 2013	0	-2	-6	1	15	5

(**Percentage change in survey comparisons** [Δ]: positive value= increase, negative value= decrease. This value is calculated as: the difference between the denominator [second measured value] and the numerator [first measured value], divided by numerator, and then multiplied by 100. First and second measured values are between successive surveys at each cross section location.)

Table 2

A

Survey at Unequal Intervals	**Top Cross Section- Left 1 (L1)**				**Top Cross Section- Left 2 (L2)**				**L1 & L2**
	Max. Top Width (m)	**Max. Depth (m)**	**Width/ Depth Ratio**	**Area (m^2)**	**Max. Top Width (m)**	**Max. Depth (m)**	**Width/ Depth Ratio**	**Area (m^2)**	**Total Area (m^2)**
2008 (4/3/08)	1.15	0.47	2.4	0.26	1.35	0.45	3.0	0.39	0.65
2009 (30/11/09)	1.25	0.58	2.1	0.29	1.65	0.59	2.8	0.64	0.93
2010 (17/4/10)	1.35	0.49	2.7	0.30	2.30	0.65	3.5	0.84	1.14
2012 (12/7/12)	1.40	0.37	3.8	0.19	2.40	0.65	3.7	0.87	1.06
2013 (7/7/13)	1.40	0.28	5.0	0.17	2.50	0.58	4.3	0.87	1.04

B

Survey Comparison	**Top Cross Section- L1**		**Top Cross Section- L2**		**L1 & L2**
	Width (% Δ)	**Depth (% Δ)**	**Width (% Δ)**	**Depth (% Δ)**	**Total Area (% Δ)**
2008- 2009	9	23	22	30	43
2009- 2010	8	-15	39	10	22
2010- 2012	4	-24	4	1	-7
2012- 2013	0	-26	4	-12	-2

(**Percentage change in survey comparisons** [Δ]: positive value= increase, negative value= decrease. This value is calculated as: the difference between the denominator [second measured value] and the numerator [first measured value], divided by numerator, and then multiplied by 100. First and second measured values are between successive surveys at each cross section location.)

Table 3

Monitoring Interval End Date	Meteorological Data						
	Max. 1 h Rain (mm) *	Mean 1 h Rain (mm) *	Mean Daily Rain (mm) **	Mean Wet Daily Rain (mm) ***	Min. Temp. (°C)	Mean Temp. (°C)	Max. Temp. (°C)
11/07/03	3.8	1.1	3.8	6.4	8.2	12.3	17.9
25/07/03	4.8	0.9	5.2	7.9	9.4	14.2	21.0
08/08/03	9.1	1.5	5.5	7.7	10.2	13.9	20.6
22/08/03	6.4	1.7	3.0	8.4	12.2	15.2	22.1
05/09/03	0.8	0.3	0.4	0.8	9.0	12.5	18.3
19/09/03	4.8	1.0	2.7	5.4	8.6	12.1	17.1
01/10/03	6.4	1.3	6.3	8.9	6.6	9.8	13.3
19/10/03	3.8	0.9	3.4	7.6	3.3	7.6	12.9
29/10/03	1.8	0.5	1.9	2.8	1.2	4.1	7.4
12/11/03	3.6	1.0	3.7	4.9	2.9	5.6	9.0
30/11/03	3.0	1.0	8.5	9.2	2.0	4.9	9.0
10/12/03	1.8	0.6	1.9	2.4	-0.2	3.4	6.2
05/01/04	6.4	1.4	7.8	13.4	-1.5	2.2	6.2

* 1 h values derived from hours in which rainfall is recorded (i.e. wet hours only)
** Mean Daily Rain- being the total rainfall depth divided by the total number of days comprising each monitoring interval
*** Mean Wet Daily Rain- the average 24 hr rainfall depth from those days in which rainfall is recorded (days= full calendar day relative to GMT; where occurring rainfall recorded during the 12h periods defining start and end days of a monitoring interval are excluded)

Table 4

Geomorphic Component	Dependent Data Sources (Time Series of Specific Process Rates) (see Figure 2 for locations)	Relationships of Independent Variable (Rainfall or Temperature Time Series) and Specific Process Rates: R^2 & (P value (significant if < 0.05))						
		Max. 1 h Rain	**Mean 1 h Rain**	**Mean Daily Rain**	**Mean Wet Daily Rain**	**Min. Temp.**	**Mean Temp.**	**Max. Temp.**
Drainage Channel- Wall	XS 1-4~	0.05 (0.47)	0.04 (0.53)	0.03 (0.54)	0.09 (0.32)	<0.01 (0.86)	<0.01 (0.81)	0.01 (0.79)
Drainage Channel- Bed	XS 1-4~	0.02 (0.62)	0.15 (0.20)	0.21 (0.11)	0.43 (0.02)	0.25 (0.08)	0.23 (0.10)	0.18 (0.14)
Main Gully- Wall	XS 5-15~	0.19 (0.14)	0.17 (0.16)	0.30 (0.055)	0.39 (0.02)	0.21 (0.12)	0.20 (0.13)	0.16 (0.17)
Main Gully- Bed	XS 5-15~	0.31 (0.049)	0.30 (0.053)	0.06 (0.42)	0.15 (0.19)	<0.01 (0.89)	<0.01 (0.90)	0.01 (0.81)
Scar- Right of Main Gully	XS 16-19~	0.03 (0.60)	<0.01 (0.94)	<0.01 (1.00)	0.03 (0.56)	0.26 (0.07)	0.28 (0.06)	0.24 (0.09)
Scar- Left of Main Gully	XS 20-24~	0.11 (0.27)	0.04 (0.49)	0.24 (0.09)	0.11 (0.28)	0.06 (0.44)	0.07 (0.37)	0.11 (0.27)

~ Full range of data sources (when available in a given monitoring interval)