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Intense rainfall and debris flows in the Lomond Hills, Fife, 11–12 August 2020

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ABSTRACT
Over the night of 11–12th August 2020, unusually intense convective rainfall triggered several debris flows along the Lomond Hills escarpment. Rainfall intensities locally exceeded an estimated 0.33% annual exceedance probability. Each debris flow had a different magnitude and physical character depending on the availability of water and sediment and the effectiveness of the vegetation buffer, such that similar-looking micro-catchments responded in different ways. The largest debris flow far exceeded the others in magnitude, extending over 1 km with a descent of 246 m and an estimated volume of c. 1500–3000 m^3, causing damage to a forestry road. Debris was entrained from a gullied relict talus, including fallen trees and incision of Lateglacial glaciofluvial sand. Deposit sedimentology and morphology demonstrate an initial debris-flow surge probably happened early in the storm coinciding with the greatest runoff generation, followed by later fluvial incision and sediment reworking. This appears to be the largest such event in the Lomond Hills for more than 90 years and may be characteristic of the landscape response to projected increases in convective rainfall intensities in twenty-first century summers.

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Convective storm; rainfall intensity; debris flow; extreme event; geomorphic threshold

Introduction

Debris flows are rapid slurry flows comprising a mixture of water and poorly sorted debris (Iverson, 1997; Morino et al. 2019). Unlike water-transport of sediment by streams, they exhibit non-Newtonian behaviour in which viscosity changes in response to stress, so that even large boulders may become buoyant in the debris flow. Debris flow activation by intense summer rainfall has been widely reported in Scotland (Ballantyne et al., 2021; Milne et al., 2015), both in the Highlands (Ballantyne, 2004) and in lowland hills (Jenkins et al., 1988). Attention to the debris-flow hazard has been acute since the 2004 Glen Ogle emergency (Milne et al., 2010; Winter et al., 2008) and with ongoing disruption to the A83 road in the south-western Highlands (Winter & Corby,

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2012). Hazard analysis has involved understanding rainfall patterns which activate debris flows (Winter et al., 2008, 2010), though a simple threshold control has proved elusive due to the complexities of antecedent conditions (Haq, 2009). Projections suggest that debris-flow events may become more frequent in eastern Scotland during the twenty-first century as increasing summer temperatures favour convective rainfall generation (Chan et al., 2018; Milne & Davies, 2007). It is, therefore, useful to record significant debris-flow events to increase the database from which connections between rainfall characteristics and landscape responses can be interpreted.

We report on an exceptional rainstorm which occurred overnight on the 11–12th August 2020 (Kendon, 2020; SEPA 2020), causing severe localised flooding across many parts of central and eastern Scotland. The storm appears to have triggered a fatal derailment after a train collided with debris on the track near Stonehaven (Rail Accident Investigation Branch, 2021), and embankment failures closed the A68 trunk route at Fala (Midlothian) and drained the Union Canal near Whitecross, flooding the railway between Edinburgh and Glasgow. In Fife, a relict coastal cliff collapse at Pettycur caused evacuation of a caravan park, and slope failure blocked the nearby A921 road and railway line. It is likely that many other small slope failures went unreported.

This paper focuses on debris flows triggered on the night of 11–12th August on the northern escarpment of the Lomond Hills (Figure 1). We present an analysis of the rainfall event, the mechanism of runoff generation and flow concentration, and describe the geomorphological response, focusing on a large debris flow in the Forthear Burn. We discuss the significance of the event in terms of projected rainfall trends and longer-term landscape evolution.

Field site

The Lomond Hills form a glacially sculpted eastward-dipping plateau created by the resistant Midland Valley Sill, which overlies Devonian and Carboniferous sedimentary rocks (MacGregor, 1996). The conical hilltops of West Lomond (522 m) and East Lomond (434 m) rise above a plateau surface between 300 and 400 m, bounded to its northern and western flanks by a steep 150–200 m escarpment (Figure 1). The lower escarpment slope is cut into aeolian sandstones of the Devonian Knox Pulpit Formation to an elevation of c. 260 m, below the scarp-forming fluvial sandstone of the Kinnesswood Formation. Above this, Carboniferous calcareous mudstones and siltstones (the Pathhead Formation) lead upwards into the Hurlet and Lower Limestone Formations, whose outcrop above the treeline is marked by former quarry workings. The Lomond Hills plateau at the study site is capped by the quartz-microgabbro Midland Valley Sill.

The surficial geology comprises a gullied talus mantle on steep slopes, composite relict colluvial cones and fans below the main gullies, and compact subglacial till and glaciofluvial sands along the slope foot. There are several significant relict slope failures, notably a large undated landslide deposit below Hoglayers (NO 194 072) of probable Lateglacial or early Holocene age. Historically, a debris flow occurred in 1928 below Craigen Gaw (Figure 1), leaving a boulder deposit that overran a stone wall (Ballantyne & Eckford, 1984), and a c. 50 m^3 debris flow in September 1985 was noted by Ballantyne (2004

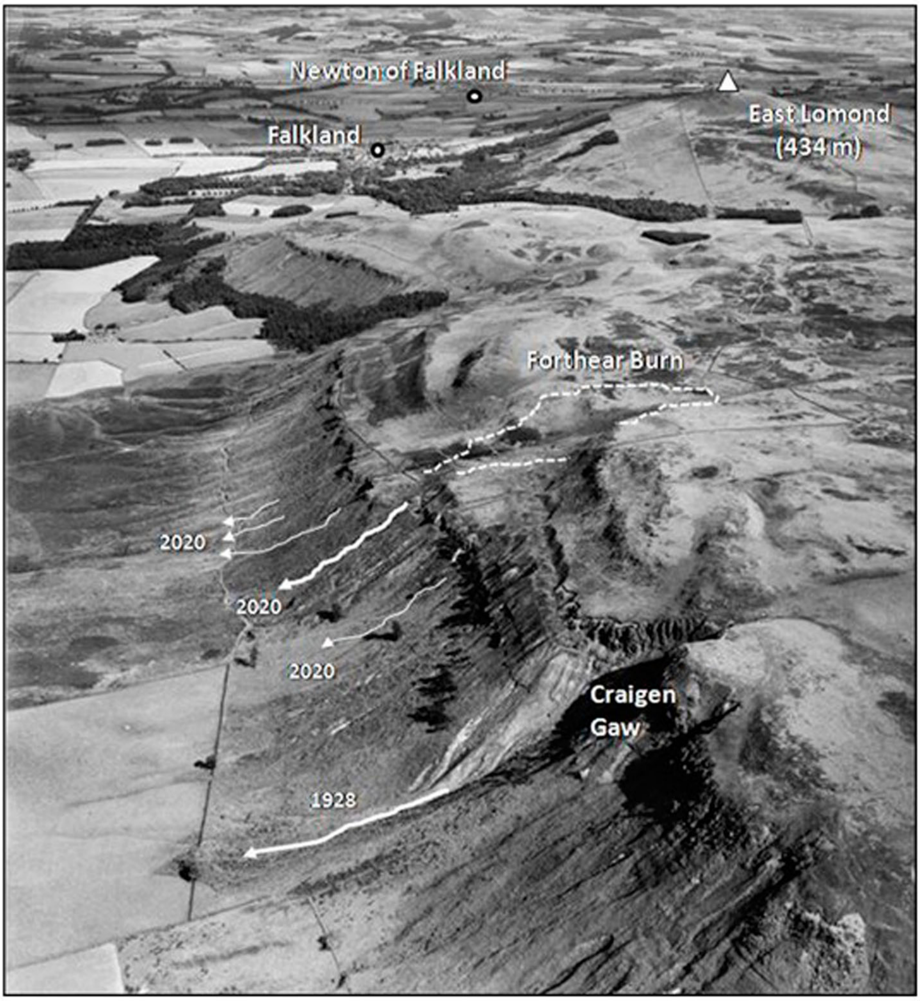

Figure 1. Oblique aerial view eastwards along the Lomond scarp. The photograph was taken on 22nd August 1952 before forestry development, which now extends to the field boundary visible immediately before Forthear Burn. The catchment area above the escarpment crest is approximated by the dashed line. The base of the escarpment is a continuous apron of relict coalescent debris cones. Known dates and sites of debris flows are shown: the August 2020 debris flows are closely clustered. (©HES Aerofilms, Canmore collection image #1297774, reproduced with permission).

and pers. comm. 2021). Soils on the plateau surface comprise peaty gleyed podzols of the Darleith soil association (Soil Survey of Scotland, 1982).

Rainfall causes and characteristics

The convection which led to the rainfall of 11–12th August 2020 was unusual in terms of the extent, duration and intensity of the precipitation generated. The convection was itself the result of strong atmospheric instability occurring during the breakdown of a period of warm and humid conditions. Prichard (2020) describes the preceding seven-day heatwave as being ‘perhaps the most intense recorded in the UK’ (p. 1).

Detailed examination of barometric pressure surfaces, the variation of wind speeds and directions with elevation, and temperature fields suggests that instability occurred at the ground surface. Lapse rates, moisture profiles and wind shear effects were all suitable for the initiation of intense convection, with topographic effects in the Southern Uplands being a likely trigger. The supplementary material included as Appendix A provides a detailed insight into the complex meteorological factors which combined to give rise to the exceptionally damaging weather conditions of this event.

Antecedent moisture conditions in Fife before the event were well within the normal range: a dry spring had been followed by slightly above-normal June and July rainfalls (Leuchars data: Met Office, 2021), and a 1-day total of 25.4 mm had already been recorded at Newton of Falkland (SEPA, 2021) on August 4th 2020. The convection formed in a broadly north–south line in the late afternoon of August 11th in the vicinity of a trough, with thunder, lightning and intense rainfall continuing over many parts of eastern Scotland for 15 h, commencing 18:00 GMT (Kendon, 2020). From an initial line extending roughly between Galashiels and Helmsdale at 18:00 on the 11th, the rainfall moved north and east, clearing the Aberdeenshire coast late the following morning.

High rainfall totals were observed in the Lothians, Falkirk, Stirling, Fife, Perth and Aberdeenshire. Based on 283 recording rain gauges across Scotland, SEPA (2020) reported extreme intensities of 57.8 mm in one hour at Dunnottar and 79 mm in just over three hours at Cheyne (near Stonehaven, Aberdeenshire), both locations lying approximately 5 km east of the derailment site noted above. Rainfall totals over eastern Scotland are shown in Figure 2, based on an interpolation of SEPA gauge data. It should be noted that for most of the gauges recording >50 mm in 24 h, 50% of the total was recorded within two consecutive hours (11 out of 18 gauges). The rain gauge data shown by Sharpe and Cranston (2021) indicate that this event did produce depth-duration values close to or slightly above the extreme threshold for Scotland (Met Office, 2021). The extreme threshold is indicative of flooding and/or landslides since it was derived using past events which caused these impacts. No stations far exceeded the extreme depth-duration threshold nor were close to the all-time record

Table 1. Extreme rainfall totals in the rainstorms of 11–12th August 2020: sites with 25 km of the Forthear Burn (data from SEPA).

		Maximum rainfall in periods of hours indicated (mm)							
Site	Distance from Forthear Burn (km)	1	2	3	4	5	6	12	24
Newton of Falkland	5.9	26.0	32.4	35.4	44.0	53.8	54.0	75.4	77.8
Rossie Farm	7.1	20.2	25.0	27.8	32.8	38.2	38.2	49.8	52.6
Fife Airport	8.6	31.8	45.8	54.2	70.4	84.4	88.0	102.0	106.6
Lathro	9.8	21.4	23.4	29.2	31.6	45.8	47.6	57.2	64.2
Baintown	15.2	2.0	2.8	3.6	4.4	4.6	4.6	5.0	5.4
Kirkcaldy	17.1	19.0	37.6	40.8	43.0	47.2	52.2	53.0	54.2
Drum	17.3	13.2	23.8	30.0	36.2	42.4	42.8	43.4	43.4
Perth Norwich Union	18.7	42.2	48.8	53.2	60.8	67.4	71.8	83.2	86.4
Kinghorn Ecology Centre	20.5	36.8	45.2	49.8	67.0	75.4	82.2	82.8	83.6
Annfield	21.4	13.2	20.6	26.2	27.2	27.2	27.2	45.6	46.6
Glenquey	22.9	20.0	31.2	40.2	51.4	61.8	73.0	74.4	78.4
Saline	23.8	14.2	24.8	31.0	34.0	38.2	41.4	43.8	44.0

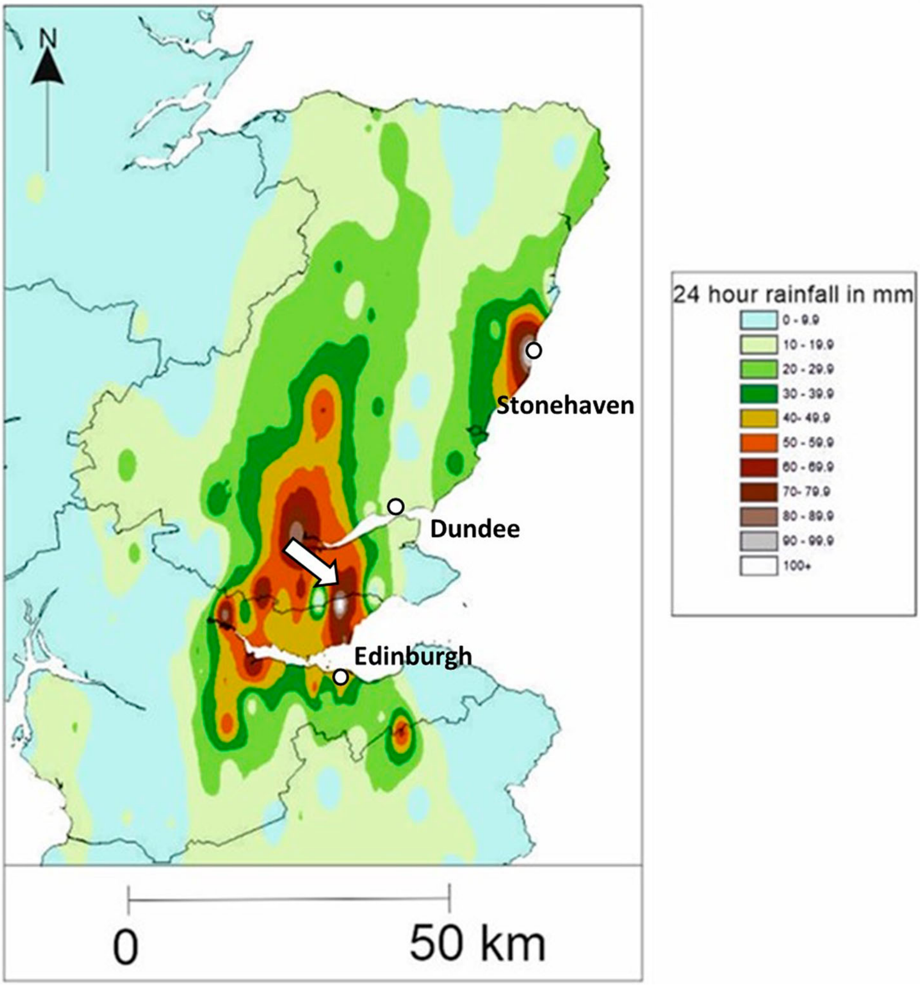

Figure 2. Maximum 24-hour rainfall totals recorded in the period 11–12th August 2020 interpolated from 283 rain gauges from the SEPA hydrometric network. (This map is available online as a colour version). The study site is indicated by the white arrow.

depth-duration values, though the 12-hour total for Fife Airport just reaches the extreme rainfall depth-duration for Scotland illustrated by Sharpe and Cranston (2021). The lack of any exceedance may be due to the distribution of rain gauges during this particular event.

Table 1 shows the maximum rainfall accumulations over a range of durations for the closest gauges to the Lomond Hills (Figure 2). Fife Airport (8.5 km SE of West Lomond) recorded the highest 6, 12 and 24-hour rainfall totals for the whole of Scotland in this period, of 88, 102 and 106.6 mm respectively. Newton of Falkland (7 km east of West Lomond) recorded 26 mm in the hour to midnight and a 24-hour total of 77.8 mm (Figure 3), while to the north, a gauge at Rossie Farm recorded a 24-hour total of 52.6 mm, including a 1-hour total of 20.2 mm also in the hour to midnight. None of the gauges in the area is at high altitude, as found more generally across Scotland

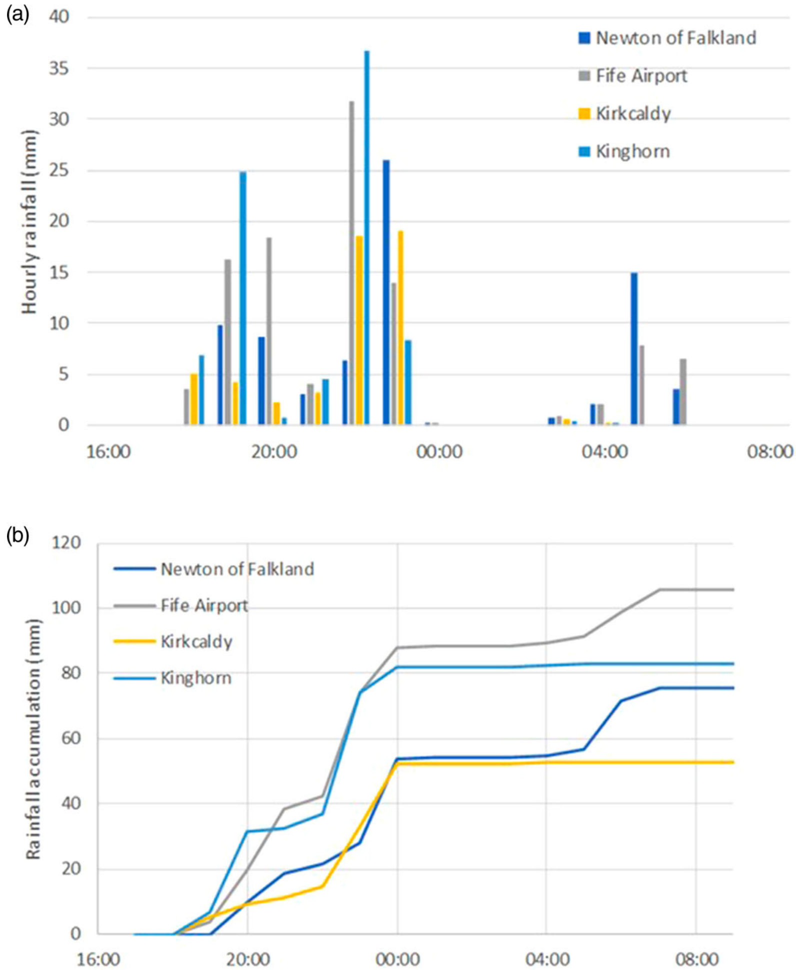

Figure 3. (A) Hourly rainfall intensities and (B) overnight accumulations 11–12th August 2020, from selected SEPA rain gauge sites in Fife (unverified SEPA data). All times are GMT.

(McGregor & MacDougall, 2009), which may hide the effects of orographic enhancement.

SEPA (2020) tentatively report that the analysis of rainfall extremes for Fife Airport leads to an annual exceedance probability of 0.33% (equivalent to an indicative return period of c. 300 years) though the confidence in this estimate is limited by the availability and content of long rainfall records in the vicinity, and by non-stationarity in a changing climate; nonetheless, the extreme nature of the event is indicated.

Spatial pattern of erosion and deposition

Observations were made on 28th August, 3rd September 2020, and on several subsequent visits. The main debris flow followed the Forthear Burn over a total length of 1124 m and a vertical descent of 246 m from the head cut to the distal toe (Figure 4). All but a very short upper section occurred within a forestry plantation. The track of the debris flow

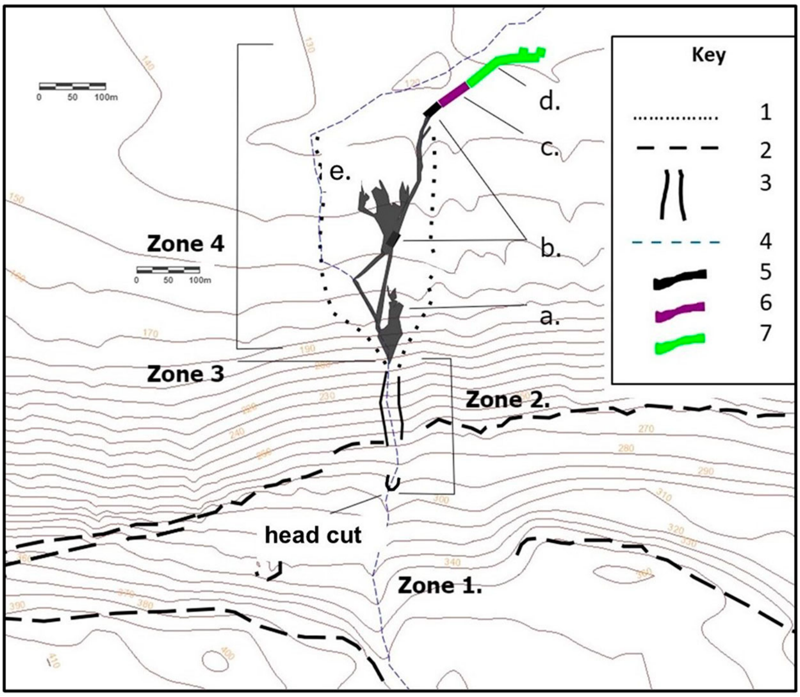

Figure 4. Geomorphology of the Forthear Burn debris flow showing the main zones 1–4 described in the text (this map is available online as a colour version). Key to symbols: 1: margin of relict debris fan; 2: bedrock scarp; 3: main escarpment gully eroded in the 2020 storm; 4: Forthear Burn; 5: extent of sediment-coated vegetation on lower forest track; 6: fluvial stratified pebbly sand; 7: fluvial stratified fine sand. 6 and 7 both exhibited late stage micro-terracing by incision. Letters 'a' to 'e' identify features mentioned in the text.

displayed distinct zones of erosion and deposition reflecting the interplay of the flow with varied substrate materials along the flow path. First, we describe the physical features of the debris flow, before reconstructing the sequence of events in process terms. Field criteria used to distinguish deposition by debris flow (non-Newtonian mass movement) and hyperconcentrated flow are adopted from Pierson (2005). These include sedimentological features including an abundance of angular clasts, non-stratified, indurated and very poorly sorted sediment with no size-grading, random dispersal of boulders and cobbles but concentrations at flow margins, thick (up to 10 mm) plastering of tree trunks, grass and fern leaves with silt to small pebble-grade sediment, and convex lobe fronts. Erosional features include widespread stripping of bark and a contrast in channel shape in Zone 3 between the debris-flow channel and the later fluvial incision (see below).

Zone 1: Unmodified upper catchment

Runoff into the gully head was from a moorland area of c. 5.9 ha of heather, grass and moss between c. 400 m elevation and the forest edge at c. 300 m (Zone 1 in Figure 4). This area comprises a dry glacial meltwater channel crossing the Lomond plateau, approximating to the line of a minor geological fault. Visible

Figure 5. Photographs from 28th August along the long profile of the Forthear Burn debris flow. (A) The upper stepped gully just below the forest edge (Zone 2). (B) Clean sandstone chute in the Knox Pulpit Formation (Zone 2, view steeply downslope). (C) Fan-head incision above the upper forest track (Zone 3). The largest boulder is c. 2 m height. (D) Two-stage incision by debris flow then fluvial erosion in Zone 3, with glaciofluvial sands in right gully wall. (E) Boulder cluster on lower forest track at the apex of the lower debris fan. (F) alluvial sands with micro-terracing covering the distal section of flow along the lower forest track.

evidence of channelised and sheetwash flow remained on the plateau after the event in the form of flattened vegetation, with no erosion, and piping exposed in the bank of the head cut.

Zone 2: Upper eroded gully (Figure 5(A,B))

The head cut of new gully erosion lay 340 m north of the watershed at an elevation of 300 m.

A low-gradient upper gully extends c. 75 m to the forest edge, entering a steep rock-floored chute which descended 75 m over a distance of 130 m at an average gradient of 32° (Zone 2 in Figure 4). A steeper stepped segment occurred where the chute crossed resistant sandstone beds. The chute was floored by clean, scoured sandstone indicating exhumation by the August 2020 flood of the gully bed from beneath a debris fill. Sediment freshly exposed in the gully walls comprised relict talus of angular sandstone boulders in a yellow-brown sandy matrix. This mantle was trimmed to a height of up to 5 m above the gully bed by the removal of the pre-existing gully fill. For most of its length, the bedrock bed formed a shallow trough in cross-section suggesting exhumation of an old runnel in the sandstone valley slope, buried by later talus accumulation.

The trunks of many conifer trees fell into the gully during the flood. These either straddled the gully or were aligned down-slope where they were moved by the flow. In places, they formed log jams against which boulders had lodged, but generally the gully bed was very clean. The steep segment terminated at a break of slope at 210 m elevation, marking the apex of a forested 6.1 ha palaeofan, crossed by an upper forest track just below the fan apex.

Zone 3: Fan head incision (Figure 5(C,D))

Above the upper forest track, the fan apex marked an abrupt transition from channelised to unconfined flow at the upslope limit of debris deposition. The full width of the fan apex was covered by debris-flow deposits comprising boulder to silt-sized sediment, with boulders and vegetation coated by gravelly silt up to 2.4 m above the fan surface on tree trunks, with clots of silty sand splashed to higher levels. Vegetation at the margins of the debris flow was shredded, flattened and plastered with sediment and woody debris (Figure 6).

Flow divided into two flow paths at the fan apex. Trees in the middle of the apex area survived but trapped a tightly packed wedge of the largest boulders entrained in the event, along with entrained tree-trunks. A lateral lobe of bouldery and woody debris spread out to the east on the forest track (Figure 7), and crossed the track to deposit a digitate sheet-fan of finer sediment and timber covering c. 7000 m^2 of forest floor ('a' in Figure 4). The larger western debris-flow path incised the fan apex above the forest track to 4 m depth to expose very coarse bouldery talus and colluvium (Figure 7(B)). Here, bark was stripped to heights of c. 1 m from upstream-facing tree trunks and silty-pebbly sand was plastered extensively over tree bark and fallen woody debris. The flow deposited a lateral bouldery lobe on the track. Below this point, the debris flow diverged again. One branch enlarged the small channel of the Forthear Burn and re-joined the vehicle track further down slope.

The majority of water and sediment followed a more direct downslope route to create a uniform 6 m-wide channel over a length of 115 m and a descent of 20 m (Figure 5(D)). The cross-sectional shape of this channel was gently concave and the channel followed a narrow footpath which was little-used and vegetated prior to the debris-flow event. This debris flow stripped vegetation and organic soil down to an iron pan at the surface of a cohesive subglacial till (Figure 6). Damage to tree trunks and sediment coatings reached over one metre up tree-trunks bordering the channel, probably from spatter. In the centre of this debris-flow channel a 2 m-long boulder was trapped by timber, demonstrating the size of clasts transported by the debris flow.

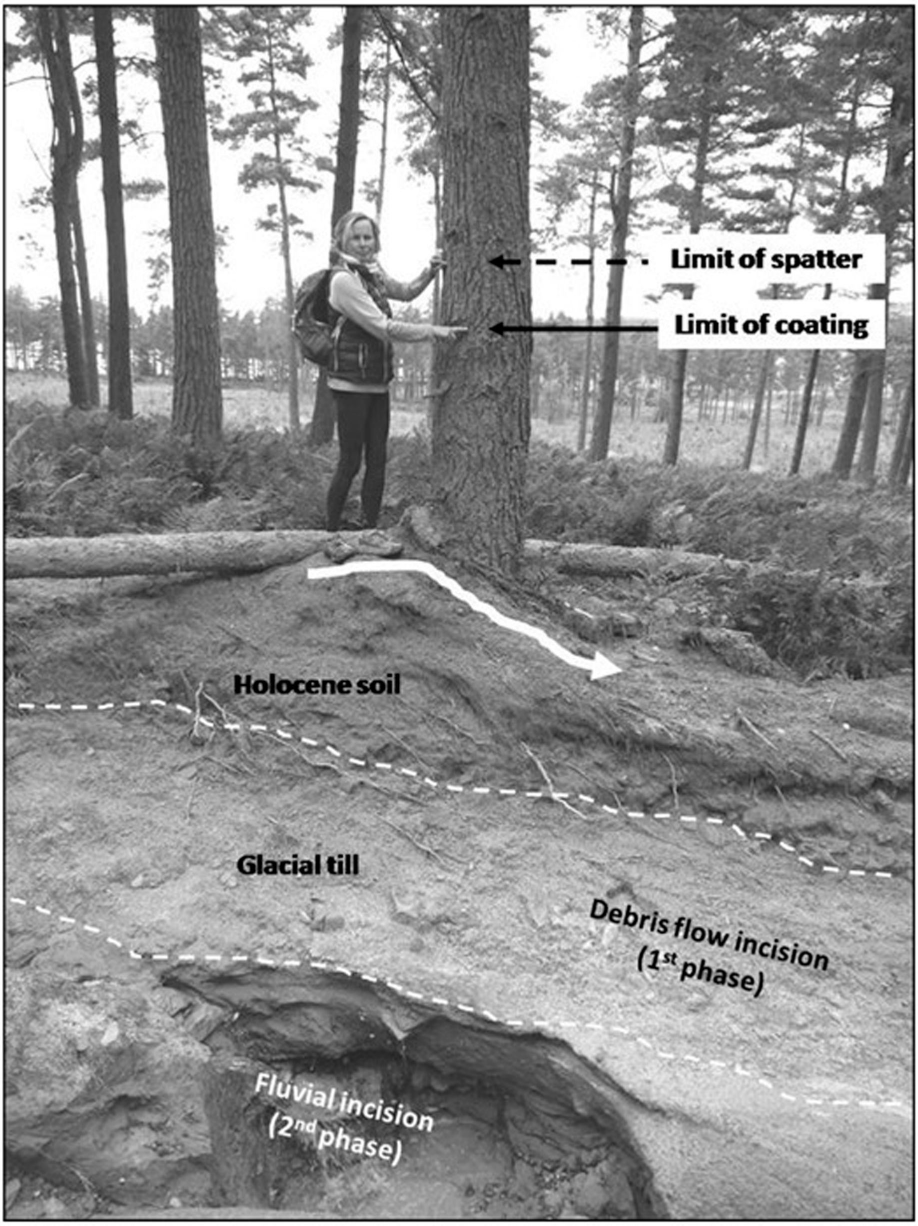

Figure 6. Channel incised into relict fan surface in Zone 3 showing the initial debris-flow path exposing resistant basal till, and the second-phase fluvial gullying of the debris-flow track. The figure is standing on the lateral levee indicating a continuous silt coating adhering to the tree bark on the upstream (left) side, with mud spatter above. The debris flow deposit is piled against the upstream side of the tree with a depositional shadow in the lee indicating greater flow viscosity at the margin.

Secondary and subsequent fluvial incision into the till exposed by debris-flow erosion was dramatic, commencing as a 2.5 m deep head cut at the upper forest track and narrowing downstream to a 1 m wide by ≤1.5 m deep inset gully (Figure 5(D)) which tapered out close to the lower forest track. At the upper end, this incision exploited a

Figure 7. (A) View west along the upper forest track of the boulder deposit with tree trunks from a secondary flow route emerging from the hillside above. The main flow path is a short distance beyond where the longer tree trunks are deposited. (B) The apex of the piedmont fan (Zone 3) below the Lomond Hills scarp slope, highlighting bark stripped from tree trunks (small dotted lines). Note the width of the debris flow track marked by sediment-coated flattened vegetation and scoured base. A large in situ boulder is outlined (B), as is the edge of the late-stage fluvial incision into a bouldery gravel substrate (dashed lines).

deposit of bedded, well-sorted glaciofluvial sands exposed up to the fan apex at 200 m elevation. Mobilisation of these sands provided a sediment source for fluvial deposition downstream (see below). The head of this channel formed a knick-point which eroded headward over subsequent weeks to cross the forest track by 10 October. A minor amount of water and sediment flowed west along the track without causing erosion, rejoining the main flow below.

Zone 4: depositional zone (Figure 5(E,F))

Below the lower forest track, the debris flow divided into two parts. In the main (western) channel the debris-flow deposited coarse silt-coated boulders and woody debris where the incised channel met the lower track to allow unconfined flow as the hydraulic radius abruptly reduced, marking the head of the main area of sediment deposition. Here the flow divided again. Below the track, a second lobate sheet-fan of finer debris-flow material was deposited over c.13,000 m^2 of forest floor (marked 'e' in Figure 4), where silt coatings and suspended matrix-supported clasts indicate viscous non-Newtonian flow within the sheet.

A secondary hyperconcentrated flow followed the line of the track north-eastwards, along which a transitional fining sequence of sediments was deposited then partly reworked. The downstream sequence consisted of bouldery gravel ('b' in Figure 4), then pebbly gravel and sand ('c'), then sorted sand in the most distal reach ('d' in Figure 4). This zone is marked by imbricate clasts clusters in its upper part and stratification of sandy deposits. Water and sediment from the lower track escaped along several narrow flow paths northwards into the lower Forthear Burn along the northern edge of the forest plantation. At the northernmost extent of deposition, a sand deposit was trapped by a small wetland basin. Transitions between these sub-zones were remarkably distinct, suggesting clear threshold controls on flow dynamics. For example, the transition from non-Newtonian slurry flow to fluvial transport was marked by the sudden disappearance of sediment coatings and a sharp transition from massive pebbly sand and gravel to sorted and micro-bedded sand deposition (the transition from 'b' to 'c' in Figure 4). The sand deposit was diagnostic of hyperconcentrated flow rather than mass movement.

Debris-flow deposits in this zone were distinguished from fluvial water-laid deposits using the field criteria outlined by Pierson (2005), and the transition zone from debris-flow to fluvial deposition was clear. In particular, thick sediment coatings on boulders, tree-trunks and fern stems remained highly visible several weeks after the debris flow occurred. Indeed, the upper edge of continuous coatings on tree trunks could be distinguished from spatter higher up the trunks. On some boulders, sediment coatings were preserved on the downstream facets of boulders but had been removed by wash from upstream facets during the event itself, indicating a later fluvial phase following the debris flow. On a return visit two months later, the finer coatings had been partially removed by rainfall but most remained.

Boulder deposition on both the upper and lower forest tracks was caused by the change in hydraulic radius from channelised to unconfined flow. Boulder size and density decreased downstream from the apex of each boulder deposit. The coarsest grades in the lower track deposit fined downstream from boulders, through cobbles and pebbles, to sand. The calibre of woody debris correspondingly decreased from tree trunks to sawn trunk/root masses to wood fragments and eventually twigs and plant material. No preserved lobate boulder front was observed even though these are a characteristic of coarse-grained debris-flow deposition. Coarse (metre-size) boulders were strongly clustered where the debris flow joined the lower forest track, but this boulder-rich deposit was reworked by high-energy wash involving removal of fines and imbrication of smaller boulders, and any lobate front which may have formed was destroyed by water action.

A later phase of fluvial reworking during the event (rather than later) was evidenced by partial reworking of the mass movement deposit on the lower forest track, whereby water washed clean a distinct strip of the debris-flow-covered track, re-exposing the original surface and live vegetation, and translocating fine sediment downstream. Water eroded a small 'gutter' gully on the true right side of the track into the underlying glacial till. The lowermost boulder sediment on the forest track additionally showed relocation of debris-flow boulders into lateral steps and imbricate clusters partially covered by washed sand.

The field evidence, therefore, points to two stages of erosion each of which left a distinct deposit. The first stage was a destructive debris flow which entrained the debris fill of the upper chute, crossing the upper forest track while carrying large tree trunks and material up to large boulder calibre. The debris flow diverged at the palaeofan apex but continued to erode a shallow channel through the wood below before crossing the lower track and dispersing finer deposits in the plantation beyond. A secondary path followed the lower track for 150 m, leaving complete and often thick sediment coatings up to 80 cm above the track surface in the upper part of this segment. The second event was fluvial incision of the palaeofan between the apex and the lower track, incising a secondary gully by entraining large quantities of erodible glaciofluvial sand, and partially reworking the debris-flow material. Hyperconcentrated flow of the second phase extended the depositional zone along the lower track by a further 250 m. Much of this material comprised sand from the incision into glaciofluvial beds, with some pebbles and aggregate entrained from the constructed forest track.

Estimates of the volumes of both the removed gully fill and the deposits are poorly constrained but are estimated to lie in the range of 1500–3000 m^3 depending on observations of deposit depths and deposit areas across the depositional zones.

Debris sources

The event was complex because debris was entrained from several sources at different times during the rainstorm, yielding very different calibres of sediment. In this way the event differs from more common hillslope debris flows where debris flows are fed by shallow translational slides in gully heads and side slopes (Ballantyne, 2004, Milne et al., 2010; Jenkins et al., 1988). There were multiple sources along the length of the debris flow:

(1) No debris was eroded from the upper catchment on the plateau above the head cut. The major debris source, and the source of all boulder debris, was the evacuation of the debris fill from the steep gully descending the escarpment. The head cut at the top of the gully has undermined a fence line to a depth of c. 3 m and extended into the plateau rim by c.75 m.
(2) The quantity of pre-existing debris filling the steep gully segment through the escarpment is not known and the steepest sections would probably not have been debris-filled. Focusing such intense rainfall into a slope length of c. 200 m at a steep gradient allowed very rapid flushing of nearly all debris from the gully in one or a series of erosive surges, probably early in the rainstorm. The clean sandstone bed would have been washed clear by the subsequent fluvial phase, removing any remaining fine material following the main debris-flow surge except for small pockets of debris protected below steep rock steps.
(3) Incision into the talus cone apex above the upper forest track remobilised a low volume but large calibre of boulders along with sandy matrix and a smaller quantity of glaciofluvial sand.

(4) Between the upper and lower tracks, basal debris-flow erosion and subsequent fluvial incision deepened the route of the main debris flow, before flow spilled out onto the lower vehicle track and spread across the forest floor.
(5) Finally, the debris-flow deposit itself provided sediment for entrainment in the fluvial second phase.

Evolution of the debris-flow event in relation to rainfall

The spatial pattern of features described above can readily be interpreted in terms of process evolution during the rainstorm. It is evident that a two-phase event took place, in which an initial debris flow was followed by fluvial incision and reworking of parts of the debris-flow deposit.

Rainfall appears to have been focused in two periods. 54 mm of rain was captured in the Newton of Falkland rain gauge between 8 pm and midnight on 11th August, half of which fell in the last hour. A further 21 mm fell between 4 and 7 am on 12th August, and in both cases the rain started and finished abruptly. The debris-flow event was not observed and its exact timing is unknown. One scenario is that the first rainfall pulse triggered the debris flow, then the second generated the fluvial phase. In this scenario, the different responses to each rainfall period reflect exhaustion of the debris in the main gully before 7 am. An alternative is that the first rainfall pulse saturated the catchment but high infiltration rates did not permit sufficient surface runoff quickly enough to release the debris flow, allowing the second pulse to generate sufficiently high pore-water pressures to cause failure in the gully-head regolith. In this area, there was evidence of overland flow and pipe flow within the regolith. If this happened early in the second rainfall period, again the initial debris-flow phase was followed by a fluvial phase once debris supply in the gully was insufficient to maintain debris flow.

During reconstruction of the forest track in November 2020, all the debris deposited on the track was removed, and new ditches and culverts were installed. By December, evidence of the event survived as fan deposits and degraded cut channels.

Discussion

Several sites in eastern Scotland recorded a month's rainfall in a matter of hours in the August 2020 storm. SEPA's (2020) estimated annual exceedance probabilities of rainfall totals in Fife are 1.0% for hourly totals of 35–40 mm, and less than 0.33% for the 4 and 12 h rainfalls recorded at Kinghorn and Fife Airport (equivalent to return periods of 1 in 100 and 1 in 300 years respectively: Table 1). Clearly, these data indicate a rare and extreme event by reference to rainfall data gathered during the second half of the twentieth century, a conclusion which accords with the dramatic geomorphological response. Such thunderstorms with heavy localised rainfall are characteristic of the breakdown of spells of warm and humid weather (Kendon, 2020). Though the accurate estimation of the return period of such events is methodologically difficult and the stated return periods are indicative only (SEPA, 2020), their significance is that the August 2020 storm represents the type of event that is projected to become more frequent during the twenty-first century.

Regional climate modelling which incorporates high spatial resolution convective rainfall is a relatively new development (Chan et al., 2018). Models project that while summer mean daily rainfall may decrease in coming decades alongside a decreased frequency of rainfall events, the intensity of summer rainfall will increase significantly as convection becomes a more common mechanism for precipitation generation in a warmer climate. Furthermore, Chan et al. (2018) suggest that such intensification will be greater in northern than in southern Britain, thus:

> … from a climate impact perspective … results here may suggest drier summers with more frequent flash flooding, which might have an effect on soil erosion, agriculture practices, and stream water quality. (Chan et al. 2018 p. 3575)

The event described in this paper suggests that such a pattern may already be manifest in the observational record.

The spatial pattern of landscape response to the rainfall distribution over the night of 11–12th August shows a close relationship between instability of natural hillslopes and extreme rainfall intensities. In Fife, debris-flow activity was tightly clustered. We observed several small translational slides and debris flows in Glenvale, 1 km south-west of West Lomond, and along a 1 km length of the Lomond Scarp. When the Pettycur landslide is also considered, the zone of geomorphological activation corresponds to rain gauges capturing >80 mm within 24 h (Figure 2), of which the majority fell in just a few hours (e.g. 88 mm in 6 h at Fife Airport). When compared to the intensity-duration threshold associated with observed debris flows in upland Scotland compiled by Winter et al. (2008), rainfall intensities over 1–12 h exceed the threshold by a factor of at least three. Rainfall on 11–12th August within 10 km of the study site demonstrably exceeded the regional threshold consistent with the dramatic geomorphological response at Forthear Burn and neighbouring sites.

Slope instability within the high-intensity rainfall zone was nevertheless localised and unpredictable at the kilometre scale. Within the narrow upland zone where debris-flows were activated, there are gullies which produced much debris (Forthear Burn most prominently) and comparable gullies that did not (e.g. Arraty Den and Craigen Gaw, 1 km east and 0.75 km west respectively). Much smaller gullies, with and without plateau catchments, variably produced very small debris flows, small turf slides, or nothing at all. This spatial pattern may be a consequence of three interrelated factors:

(1) Very localised extreme rainfall intensities, varying possibly over a few hundred metres and not captured by the rain gauge network;
(2) Topography favouring erosion only where critical entrainment thresholds were exceeded, where runoff from gentle plateau catchments was concentrated into steep escarpment gullies;
(3) The presence of an accumulated debris fill within the gully available for mobilisation.

The Forthear Burn generated by far the largest debris flow in the Lomond Hills because the local rainfall intensity was sufficient to enable the geomorphological threshold (imposed by vegetation, soil cover, and the coarse calibre of the gully fill) to be surpassed.

The rate of post-event gully recharge may be significant as it decouples meteorological (rainfall) return periods from geomorphological (debris flow) return periods (Brayshaw & Hassan, 2009; Jakob et al., 2005; Martin et al., 2017). Thus, runoff events capable of mobilising gully-fill debris will generate debris flows. However, if such rainfall events happen frequently, fewer and smaller debris flows will be generated where rates of gully refill are slow. The resulting spatial pattern of debris-flow activity resulting from a single rainstorm will thereby reflect the variable state of debris accumulation in different gullies prior to that storm. It may be that the Forthear Burn was very active in 2020 *because* it did not generate a debris flow in the 1928 storm, in contrast to Craigen Gaw which was activated in 1928 but not in 2020.

The volume of water flowing into the head of the Forthear Burn in 2020 combined with the volume and variety of sediment sources was sufficient to generate the 'classic' full sequence of debris-flow features during the event. These were an initial debris-rich surge removing the gully fill to generate Coulomb-type behaviour of a destructive boulder-rich sediment slurry dominated by grain-to-grain contacts (Iverson, 2003), eroding a path through the forest, entraining boulders and tree trunks and coating surrounding trees and vegetation with silt, and spreading onto the fan. This was followed by a water-rich (Newtonian) phase of incision of the initial debris-flow path and hyperconcentrated suspension of sand determined by the inherent viscosity of the sand-water mixture, to lay down the sand deposit along the lower forest track.

Conclusions

Summer climate in eastern Scotland is projected to experience more frequent intense rainstorms driven by convection. This single-event case study demonstrates what geomorphological change can occur under extreme conditions, thereby contributing to our understanding of how the landscape may already be reacting to extreme downpours. Empirical studies of contemporary extreme weather events provide a valuable contribution to a more general understanding of both the nature of local geomorphological thresholds and of hazardous locations in the landscape.

The rainstorm of 11th–12th August 2020 was generated by a north–south alignment of convection cells carried across Fife on a southerly airflow, delivering intense rainfall over a single night during which recorded rainfall intensities locally exceeded 30 mm h^{-1}. The landscape response was spatially variable, the most spectacular landform response being the >1 km-long debris flow in the Forthear Burn. The physical characteristics of the sediment deposits indicated an initial and destructive debris-flow surge carrying metre-scale boulders and tree trunks, followed by a phase of incision of the debris-flow track and sand transport as a hyperconcentrated flow. The debris flow demonstrated classic indicators of slurry-type mass movement which contrasted with the washed-out bedded sand of the second phase. The hazard potential of such a violent event was not realised simply because the debris flow occurred overnight when the woodland trails were empty.

Model projections of increased summer rainfall intensity may be inferred to increase the likelihood of similar debris flows through the coming century. However, the geomorphological response is complex; a wider survey of the Lomond Hills escarpment revealed variations between individual hillslope gullies in their catchment characteristics and sediment availability. This indicates that neighbouring slopes and gullies have a variable likelihood of releasing storm-generated debris flows making precise hazard assessment difficult.

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References

Ballantyne, C. K. (2004). *Geomorphological changes and trends in Scotland: debris flows*. Scottish Natural Heritage Commissioned Report No. 052 (ROAME NO. F00AC107A), 19 pp.

Ballantyne, C. K., Black, A. R., Ferguson, R., Gordon, J. E., & Hansom, J. D. (2021). Scotland's changing landscape. In Ballantyne, C.K. & Gordon, J. E. (Eds.), *Landscapes and landforms of Scotland* (pp. 97–114). World Geomorphological Landscapes. https://doi.org/10.1007/978-3-030-71246-4_597.

Ballantyne, C. K., & Eckford, J. D. (1984). Characteristics and evolution of two relict talus slopes in Scotland. *Scottish Geographical Magazine*, *100*(1), 20–33. https://doi.org/10.1080/00369228418736575

Brayshaw, D., & Hassan, M. A. (2009). Debris flow initiation and sediment recharge in gullies. *Geomorphology*, *109*(3–4), 122–131. https://doi.org/10.1016/j.geomorph.2009.02.021

Chan, S. C., Kahana, R., Kendon, E. J., & Fowler, H. (2018). Projected changes in extreme precipitation over Scotland and Northern England using a high-resolution regional climate model. *Climate Dynamics*, *51*(9–10), 3559–3577. https://doi.org/10.1007/s00382-018-4096-4

Haq, M.R. (2009). *Development of a remote sensing and GIS-based landslide susceptibility model for Scotland* [Unpublished PhD thesis]. University of Dundee.

Iverson, R. M. (1997). The physics of debris flows. *Review of Geophysics*, *3*(3), 245–296. https://doi.org/10.1029/97RG00426

Iverson, R. M. (2003). The debris flow myth. In D. Rickenmann, & C.-L. Chen (Eds.), *Debris flow hazards mitigation: Mechanics, prediction and assessment* (pp. 303–314). Millipress.

Jakob, M., Bovis, M., & Oden, M. (2005). The significance of channel recharge rates for estimating debris-flow magnitude and frequency. *Earth Surface Processes and Landforms*, *30*(6), 755–766. https://doi.org/10.1002/esp.1188

Jenkins, A., Ashworth, P. J., Ferguson, R. I., Grieve, I. C., Rowling, P., & Stott, T. A. (1988). Slope failures in the Ochil Hills, Scotland, November 1984. *Earth Surface Processes and Landforms*, *13*(1), 69–76. https://doi.org/10.1002/esp.3290130109

Kendon, M. (2020). *Thunderstorms north-east Scotland 11–12 August 2020*. Met Office Past Weather Events Report. Retrieved December 14, 2020. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2020/2020_07_august_rain.pdf.

MacGregor, A. R. (1996). *Fife and angus geology*. Pentland Press. 291 pp.

Martin, Y. E., Johnson, E. A., & Chaikina, O. (2017). Gully recharge rates and debris flows: A combined numerical modelling and field-based investigation, Haida Gwaii, British Columbia. *Geomorphology*, *278*, 252–268. https://doi.org/10.1016/j.geomorph.2016.11.012

McGregor, P., & MacDougall, K. (2009). A review of the Scottish rain-gauge network. *Proceedings of the Institution of Civil Engineers: Water Management*, *162*(2), 137–146. doi://10.1680/wama.2009.162.2.137

Met Office. (2021). Historic station data. Retrieved August 27, 2021. https://www.metoffice.gov.uk/research/climate/maps-and-data/historic-station-data.

Milne, F. D., Brown, M. J., Davies, M. C. R., & Cameron, G. (2015). Some key topographic and material controls on debris flows in Scotland. *Quarterly Journal of Engineering Geology and Hydrogeology*, *48*(3–4), 212–223. https://doi.org/10.1144/qjegh2013-095

Milne, F. D., Brown, M. J., & Werritty, A. (2010). A hazardous channelized debris flow in Glen Ogle, Stirlingshire. *Scottish Journal of Geology*, *46*(2), 181–189. https://doi.org/10.1144/0036-9276/01-409

Milne, F. D., & Davies, M. C. R. (2007). Control of soil properties on the Scottish debris flow geohazard and implications of projected climate change. *Landslides and climate change: Challenges and solutions*. Proceedings of the International Conference on Landslides and Climate Changes, Ventnor, Isle of White (pp. 121–127).

Morino, C., Conway, S. J., Balme, M. R., Hillier, J., Jordan, C., Sæmundsson, Þ., & Argles, T. (2019). Debris-flow release processes investigated through the analysis of multi-temporal LiDAR datasets in north-western Iceland. *Earth Surface Processes and Landforms*, *44*(1), 144–159. https://doi.org/10.1002/esp.4488

Pierson, T. C. (2005). *Distinguishing between debris flows and floods from field evidence in small watersheds*. United States Geological Survey, Fact Sheet 2004-3142, 4 pp.

Prichard, B. (2020). *August 2020: Weather log*. Royal Meteorological Society. https://doi.org/10.1002/wea.3570.

Rail Accident Investigation Branch. (2021). *Derailment of a passenger train at Carmont, Aberdeenshire 12 August 2020*. Rail Accident Investigation: Interim Report. Report IR1/2021. Retrieved June 8, 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/978504/IR012021_210419_Carmont.pdf.

SEPA. (2020). *The flash floods of 11 and 12 August 2020 in Central and Eastern Scotland*. Scottish Environment Protection Agency report. Retrieved December 14, 2020. https://www.sepa.org.uk/media/536333/the-flash-floods-of-11-and-12-august-2020.pdf.

SEPA. (2021). *Rainfall data for Scotland*. Scottish Environment Protection Agency data. Retrieved August 27, 2021. https://www2.sepa.org.uk/rainfall/.

Sharpe, M., & Cranston, M. (2021). Extreme rainfall in Scotland on 11 and 12 August 2020: Evaluation of impact-based rainfall forecasts. *Weather*, *76*(8), 254–260. https://doi.org/10.1002/wea.3981

Soil Survey of Scotland. (1982). *Sheet 7: South-East Scotland. 1:250,000 map*. Macauley Land Use Research Institute. Retrieved December 16, 2020. http://www.hutton.ac.uk/

Winter, M. G., & Corby, A. (2012). *A83 rest and be thankful: Ecological and related landslide mitigation options*. Project Report PPR636, Transport Research Laboratory, Transport Scotland, 26 pp.

Winter, M. G., Macgregor, F., & Dempsey, P. (2010). Debris flow, rainfall and climate change in Scotland. *Quarterly Journal of Engineering Geology and Hydrogeology*, *43*(4), 429–446. https://doi.org/10.1144/1470-9236/08-108

Winter, M. G., Macgregor, F., & Shackman, L. (2008). *Scottish road network landslides study: Implementation*. Transport Scotland.