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Geomorphological changes and trends in Scotland: debris-flows

(ROAME No. F00AC107A)

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COMMISSIONED REPORT

Summary

Geomorphological changes and trends in Scotland: debris-flows

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Background

As part of its environmental audit programme, SNH is investigating changes and trends for natural heritage reporting and development of indicators. Changes in geomorphological processes are an integral part of the natural heritage. The aim of this report, part of a series on geomorphological processes, is to document and analyse trends in debris-flows.

The term *debris-flow* refers to the rapid downslope flow of a mixture of debris and water, and is also used to refer to the tracks of individual flows. Movement is distinct from fluvial transport in that the entire sediment-water mixture undergoes flow *en masse*. Two types of debris-flow are widespread: *hillslope flows*, which occur on open slopes, and *valley-confined flows*, which originate in bedrock gullies. Most hillslope flows involve <$60m^3$ of sediment, though valley-confined flows may carry >$1000m^3$ of sediment. Flow tracks are characterised by upslope gully erosion, and downslope deposition of parallel levées of bouldery debris and terminal lobes, tongues or fans of coarse sediment.

Debris-flows are generated by intense rainstorms that cause saturation of sediment on slopes and in gullies, leading to failure and flow. There is some evidence that flow activity has undergone a significant increase within the past 200–300 years, though the possible causes of such an increase remain contentious.

Main findings

1. Debris-flows are limited to areas of steep relief with valley-side slopes steeper than 30° or deep bedrock gullies. Flow distribution in areas of steep relief is restricted to slopes that support a cover of unconsolidated sediment (till, talus or regolith), especially sediment with a coarse sandy matrix.

2. Debris-flows have occurred intermittently at flow-susceptible sites over much or all of the past 7000 years, but there is geomorphological evidence for more frequent and more extensive hillslope flow activity within the past few centuries.

3. Both lichenometric evidence and accounts of debris-flow events over the past 50 years suggest that the average recurrence interval of flow events at flow-susceptible sites is of the order of <10 years to a few decades.

4. Major flow events have been triggered by rainfall intensities of 60–80mm in 24 hours, though not all prolonged high-intensity rainstorms trigger widespread debris-flow activity, even on flow-susceptible slopes; antecedent moisture conditions are critical.

5. No dominant cause of an increase in debris-flow activity over the past few centuries has been identified. Possible causes include an increased incidence of exceptional rainstorm events, reduction in the stability of slopes during storm events due to progressive pedogenesis (podzolisation), woodland clearance, heather burning and overgrazing.

6. Most flows occur in remote parts of the Scottish Highlands, and pose no significant threat to life or structures, but in the past 50 years a few debris-flow events have caused damage to roads, bridges, culverts and buildings.

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1 INTRODUCTION

Environmental audit in Scottish Natural Heritage (SNH) is being developed to assess status, identify trends and explain the main factors influencing change. Natural heritage trends are therefore being analysed and documented for natural heritage reporting and development of indicators (Mackey *et al*, 2001). Changes in geomorphological processes are an integral part of the natural heritage. This report, part of a series on geomorphological processes, addresses trends in debris-flows, an important component of slope processes. It provides a review and analysis of the available information and sources used to compile the SNH Trend Profile for debris-flows.

The term *debris-flow* refers to the rapid downslope flow of poorly-sorted debris mixed with water. The term is also used to refer to the tracks of individual flows. A debris-flow in progress resembles rapidly-moving wet cement with boulders being carried along at the surface at velocities of several metres per second, though water content rarely exceeds 10–30% by weight. Debris-flow differs fundamentally from stream flow in that the mixture of sediment and water flows downslope *en masse*. The movement of most debris-flows in Scotland is dominated by cohesionless grainflow, in which the momentum of flow is maintained by interparticle collisions, with boulders attaining partial buoyancy in a moving mass of mud (Blikra and Nemec, 1998).

Debris-flows in Scotland are important in three contexts. First, in many mountain areas they play the dominant role in modifying the form of steep valley-side slopes, primarily by cutting deep gullies in the hillslope sediment cover and depositing spreads of debris at the slope foot. Second, they have been responsible for stripping soil and vegetation cover, often exposing the underlying bedrock and reducing grazing potential. Third, debris-flows represent a potential hazard to structures and communications in slope-foot locations.

Two types of debris-flow are widespread on steep mountain slopes in Scotland: *hillslope flows*, which occur on open slopes, and *valley-confined flows*, which originate in bedrock gullies and are channelled for at least part of their length along the gully floor. The two categories are transitional; many valley-confined flows debouch on to open ground in their lower reaches, and hillslope flows often follow shallow gullies cut in valley-side drift, talus or regolith (Figure 1). A third category of *catastrophic debris-flows* is represented at a few sites where rock-slope failure has resulted in the runout of large debris lobes (Ballantyne and Eckford, 1984; Ballantyne, 1992). Such catastrophic flows are ancient features that reflect stress-release due to deglacial unloading and consequent sliding failure in rock masses, and are not considered further here.

Hillslope and valley-confined debris-flows tend to follow long, narrow tracks. The upper, erosional section of the flow consists of a gully that is continued downslope by parallel levées of dominantly coarse debris that enclose the track of the flow and often terminate downslope in one or more lobes of bouldery debris. Gullies excavated in unconsolidated deposits on the upper slope often decline in width and depth downslope, and levées usually diminish in height towards the slope foot. The track between individual levées in the runout zone is often little affected by the passage of the flow, and may support flattened but otherwise undisturbed vegetation (Figure 1).

The form of sediment runout reflects flow viscosity, which is highly sensitive to water content (Blikra and Nemec, 1998). Low-viscosity flows with high water content usually form elongate tongues of debris (Figure 1), whereas high-viscosity flows with low water content tend to spread out over footslopes as broad lobes. In Scotland, the former are far more common than the latter. In a survey of the dimensions of

Figure 1 Debris flow in the Lairig Ghru, Cairngorm Mountains. This flow is transitional between the hillslope and valley-confined types. Earlier flows can be seen to the right of the main flow. (Photo © C.K. Ballantyne)

780 debris-flows in the Scottish Highlands, Innes (1985) found that though low-viscosity hillslope debris-flows contain up to 240m^3 of debris, 60% involve <20m^3 of sediment and 90% involve <60m^3 of sediment. In contrast, a high-viscosity valley-confined flow in Glen Feshie was calculated to have transported >1600m^3 of sediment (Brazier and Ballantyne, 1989). Where successive debris-flows have followed the same track, the accumulated sediment forms a *debris cone*. Debris cones typically have gradients of 12–25° and are particularly prominent at the foot of rock gullies that have channelled valley-confined flows on to the footslope zone.

Debris-flow deposits typically comprise matrix- or clast-supported diamictons in which cobbles and boulders are embedded in fine sediment. Many individual flows exhibit inverse (ie coarsening-upwards) grading due to dispersive stresses that push the largest boulders to the surface and sides of the flow. The tongue-shaped lobes of low-viscosity debris-flows typically consist of a coarse, clast-supported frontal zone that extends upslope into a thinner 'tail' (Blikra and Nemec, 1998). Other sediments associated with debris-flows include beds of massive pebble-sands representing hyperconcentrated flow (ie intermediate between debris-flow and flood torrent flow), and thin stratified deposits of silt and sand associated with outwash of fine sediment following flow immobilisation (Matthews *et al*, 1999).

Debris-flows are generated in two main ways. On open hillslopes or gully sides, initial failure usually takes the form of a shallow (0.3–3.0m thick) translational (slab) slide, often over the underlying bedrock. Some translational slides remain intact and travel only short distances downslope, but others undergo a transition from sliding to debris-flow due to loss of internal frictional strength and consequent liquifaction and remoulding of the sliding mass. Within gullies, however, flood torrents may be transformed into valley-confined debris-flows by the addition of sediment from the gully floor and walls (Bovis and Dagg, 1992), or by failure of gully-floor debris dams during periods of flood runoff (van Steijn *et al*, 1988).

Irrespective of the mode of flow initiation, debris-flows are generated when a build-up of porewater pressures in unconsolidated sediments causes a reduction in shearing resistance, leading to failure and sediment flow. Although this may occur due to rapid snowmelt (Ballantyne and Benn, 1994), all documented instances of recent debris-flow activity in Scotland are associated with high magnitude rainstorms (Common, 1954; Baird and Lewis, 1957; Innes, 1982; Jenkins, *et al*, 1988; Luckman, 1992). Debris-flow initiation cannot, however, be directly related to rainstorm magnitude (intensity and duration), because of the effect of antecedent soil moisture conditions, in other words the soil moisture content and depth of the water table prior to the onset of the storm (Church and Miles, 1987). Thus, whereas there are recorded instances of widespread debris-flow activity in Scotland triggered by rainfall intensities of 60–80mm in 24 hours, a rainfall intensity of 140mm in 24 hours over An Teallach in NW Scotland in September 1981 following a dry month (Acreman, 1983) generated only a single small valley-confined flow on the mountain.

2 DISTRIBUTION AND SPATIAL TRENDS

Figure 2 indicates the main areas of debris-flow activity in Scotland, based on an airphoto search (using 1959–1962 photography) by Innes (1982, 1983a) for the presence of debris-flows within 100km^2 grid squares. Although this map under-represents the true distribution of debris-flows, it highlights areas of endemic debris-flow activity such as the NW Highlands, Skye, Rum, Rannoch-Glencoe-Lochaber and the Cairngorms. Equally notable is the absence of recorded debris-flows in some areas of high relief, such as the mountains of the Outer Hebrides, Morvern, Knoydart, part of Argyll and the SE Grampians, together with the lava scarps of the Midland Valley and the hills of the Southern Uplands. Though occasional debris-flows are present in these areas, they are much less common than in the areas where Innes' survey detected geomorphological evidence for debris-flow activity (Ballantyne, 1986).

The distribution of debris-flows in Scotland is primarily determined by slope gradient. Surveyed hillslope flows in Scotland have source areas on slopes of 30–46°, with most starting on gradients of 32–42° (Ballantyne, 1981; Innes, 1983b). Open hillslopes with gradients <30° rarely support debris-flows. Though valley-confined flows may be initiated on gully floors with gradients of 20° or less (Innes, 1983b), such gullies are usually cut into steep rockwalls. Debris-flows in Scotland are thus retricted to areas of steep relief, particularly the glacially-steepened slopes of corrie headwalls, glacial troughs and scarps.

Within areas of glacially-steepened slopes, debris-flow distribution is largely determined by sediment availability. Three sources of sediment feed debris-flows in Scotland, namely regolith derived from weathering of underlying bedrock (Innes, 1982, 1986; Reid, 2001), till deposits mantling steep hillslopes (Baird and Lewis, 1957; Jenkins *et al*, 1988; Brazier and Ballantyne, 1989; Ballantyne and Benn, 1996; Curry, 1999, 2000a, 2000b) and talus accumulations composed of debris that has fallen from cliffs upslope (Salt and Ballantyne, 1997; Hinchliffe, 1998, 1999; Hinchliffe *et al*, 1998). Debris-flows, particularly hillslope flows, are therefore rare in areas of extensive glacial scouring where regolith, drift or talus cover is thin or absent on valley-side slopes, thus accounting for their scarcity in the mountains of the Outer Hebrides, Knoydart, Morvern and Argyll (Figure 2).

A more subtle control on debris-flow distribution is sediment texture. Ballantyne (1981) and Innes (1982, 1983b) have shown that the spatial density of hillslope flows in the Scottish Highlands is much greater on slopes mantled by regolith or drift with a coarse-grained cohesionless, sandy matrix. Hillslope flows are consequently much more widespread on slopes underlain by lithologies such as sandstone and granite (which yield abundant coarse sand on weathering, and are often mantled by sandy till) than on slopes underlain by mica-schists (which are mantled by drift or regolith containing a much higher proportion of fine sand and silt). Figure 3 shows the contrast in flow density between upper Glen Einich in the Cairngorms, which is underlain by granite, and Glen Docherty in the NW Highlands, which is underlain by mica-schist. Though Glen Docherty supports a density of debris-flows that is unusually high for terrain underlain by schists, the density of flows here is less than one-third of that for upper Glen Einich (Table 1). The susceptibility of coarse-grained sediments to debris-flow has been attributed to high infiltration rates, which permit a rapid rise in porewater pressures during rainstorms (Innes, 1982; Ballantyne, 1986). The scarcity of hillslope debris-flows on many mountains underlain by schistose rocks in the Highlands or shales in the Southern Uplands (Figure 2) probably reflects the relatively fine-grained nature of the regolith or drift mantling steep slopes in these areas.

Figure 2 **Distribution of debris flow activity in Scotland based on presence or absence of debris flows within 10km x 10km grid squares, and showing location of sites mentioned in the text. Based on Innes (1983a), with additions. (Copyright 2002 © John Wiley & Sons Ltd. Reproduced with permission)**

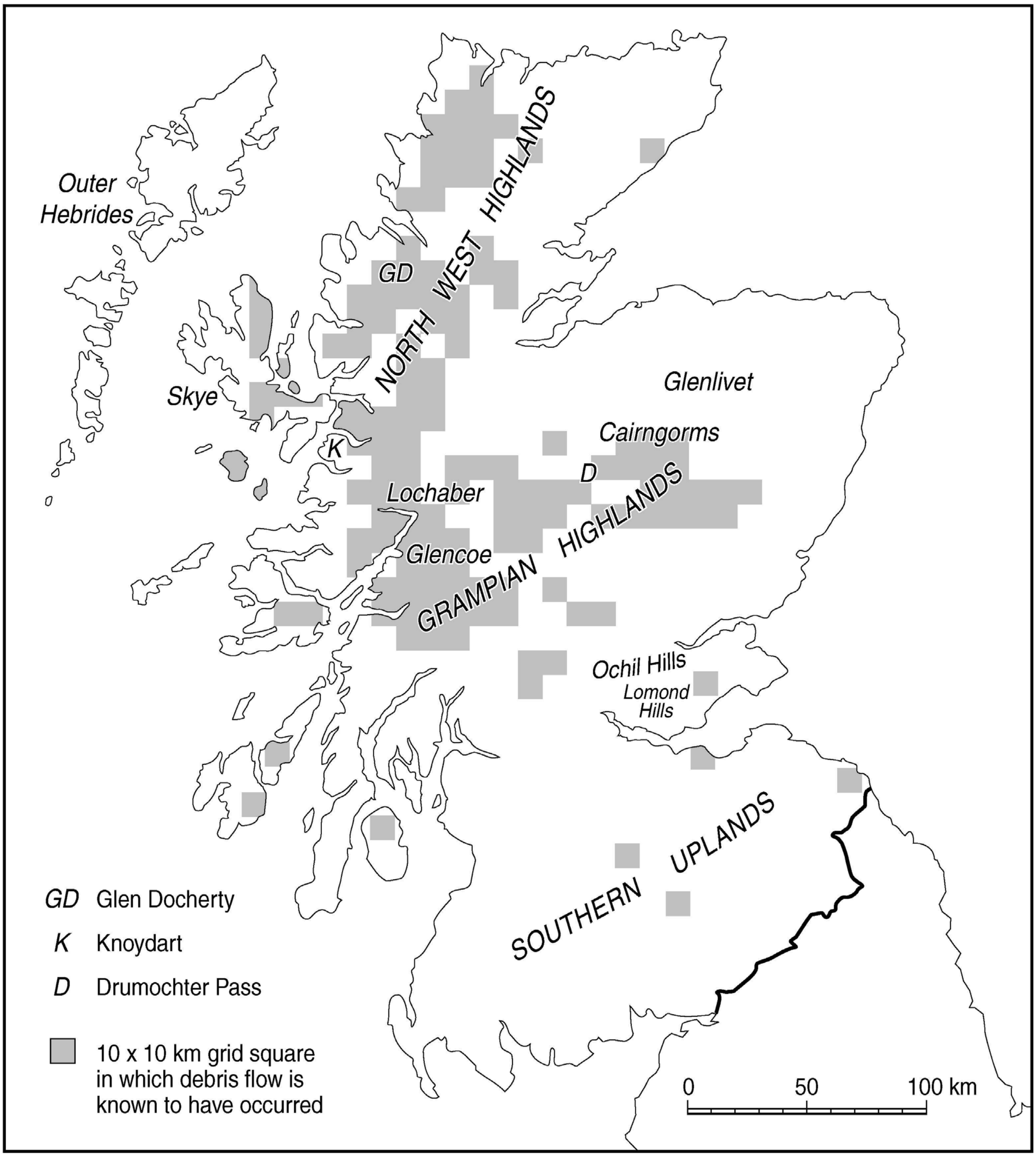


Figure 3 Maps of debris-flow landforms and deposits on terrain underlain by granite (upper Glen Einich, left) and mica-schists (Glen Docherty, right). Adapted from Curry (1999) with permission

Airphoto and documentary evidence suggests that the spatial density of debris-flows on some slopes has increased over the last 50 years, for example in Drumochter Pass and the Cairngorms (Innes, 1982; Luckman, 1992). There is also documentary evidence for recent extension of debris-flow activity into previously unaffected areas, such as Glenlivet (Brooks *et al*, 1993) and parts of the Ochil Hills scarp (Jenkins *et al*, 1988).

Table 1 Spatial density of debris-flow gullies on slopes underlain by granite and mica-schist (modified from Curry, 1999)

Site	**Lithology**	**Gully density**
Glamaig, Skye	Granite	25 gullies per kilometre
Beinn Dearg, Skye	Granite	20 gullies per kilometre
Upper Glen Einich, Cairngorms	Granite	13.7 gullies per kilometre
Glen Docherty, NW Highlands	Mica-schist	3 gullies per kilometre
Drumochter Pass, Eastern Grampians	Mixed schists	2.6 gullies per kilometre

3 TEMPORAL TRENDS

Three sets of data are relevant to identifying temporal trends in debris-flow activity: (1) stratigraphic evidence and radiocarbon dating of organic horizons underlying or overlying debris-flow deposits exposed in section on hillslopes or debris cones, which yield data on flow frequency on a millennial timescale; (2) lichenometric data relating to the frequency of debris-flow activity over the past 500 years; and (3) documentation relating to debris-flow events over the past 50 years. These three sources of data are summarised in turn below, then synthesised in terms of temporal trends and the return period of debris-flow events.

3.1 Stratigraphic evidence and radiocarbon dating

Stratigraphic evidence from sites in the Scottish Highlands indicates that reworking of till by debris-flows was widespread after ice-sheet deglaciation (Bennett, 1999) and during and after ice retreat at the end of the Loch Lomond Stade approximately 11,500 years ago (Benn, 1991, 1992; Bennett, 1999; Dix and Duck, 2000). Such widespread *paraglacial* (glacially-conditioned) debris-flow activity reflects the instability of steep drift-mantled slopes immediately after deglaciation, and probably lasted no more than a few centuries (Ballantyne and Benn, 1994, 1996). However, radiocarbon dating of debris-flow deposits exposed in sections in drift- and regolith-mantled hillslopes, talus slopes and debris cones at nine sites (Figure 4) has also revealed evidence for intermittent debris-flow activity over much of the past 7000 years, long after the initial phase of paraglacial sediment reworking. Radiocarbon dating of organic sediments (buried peat layers and organic soils) immediately underlying debris-flow deposits or associated hyperconcentrated flow deposits yields a maximum age for the overlying deposit. In most instances the contact between the two is conformable, indicating that little or no erosion of the underlying peat or soil has occurred, so that the radiocarbon age provides a close estimate of the timing of the debris-flow event. Radiocarbon ages obtained from the base of organic horizons immediately overlying debris-flow units provide a minimum age for individual flow units.

Figure 5 summarises the radiocarbon dating evidence for the timing of debris-flow activity in the Scottish Highlands over the past 7000 years. Sampling and stratigraphic details are given in Innes (1982, 1983c), Brazier *et al* (1988), Brazier and Ballantyne (1989), Hinchliffe (1998, 1999), Curry (1999, 2000a, 2000b) and Reid (2001). The dates summarised in Figure 5 have been calibrated using the CALIB 4.3 programme (Stuiver and Reimer, 1993). The length of each horizontal bar encompasses the 95% confidence limits for each age estimate.

Although the data indicate that debris-flow activity has occurred throughout most of the past 7000 years, clustering of dates suggests that periods of enhanced debris-flow activity may have occurred within the past 700 years, 1700–2700 years ago and possibly 3400–4400 and 5900–6400 years ago, with intervening periods of reduced activity. Over a millennial timescale, such variations in the incidence of dated debris-flow activity may be related to the frequency of extreme rainstorm events. However, statistical analysis of the data summarised in Figure 5 has not been carried out, and it is possible that the apparent clustering of dates does not depart significantly from a random distribution. The absence of radiocarbon dates relating to the period prior to 7000 years ago probably reflects the difficulty of obtaining datable material from the lowest parts of thick sequences of debris-flow deposits rather than an absence of earlier debris-flow activity.

Figure 4 Sites where radiocarbon ages have been obtained on debris-flow deposits

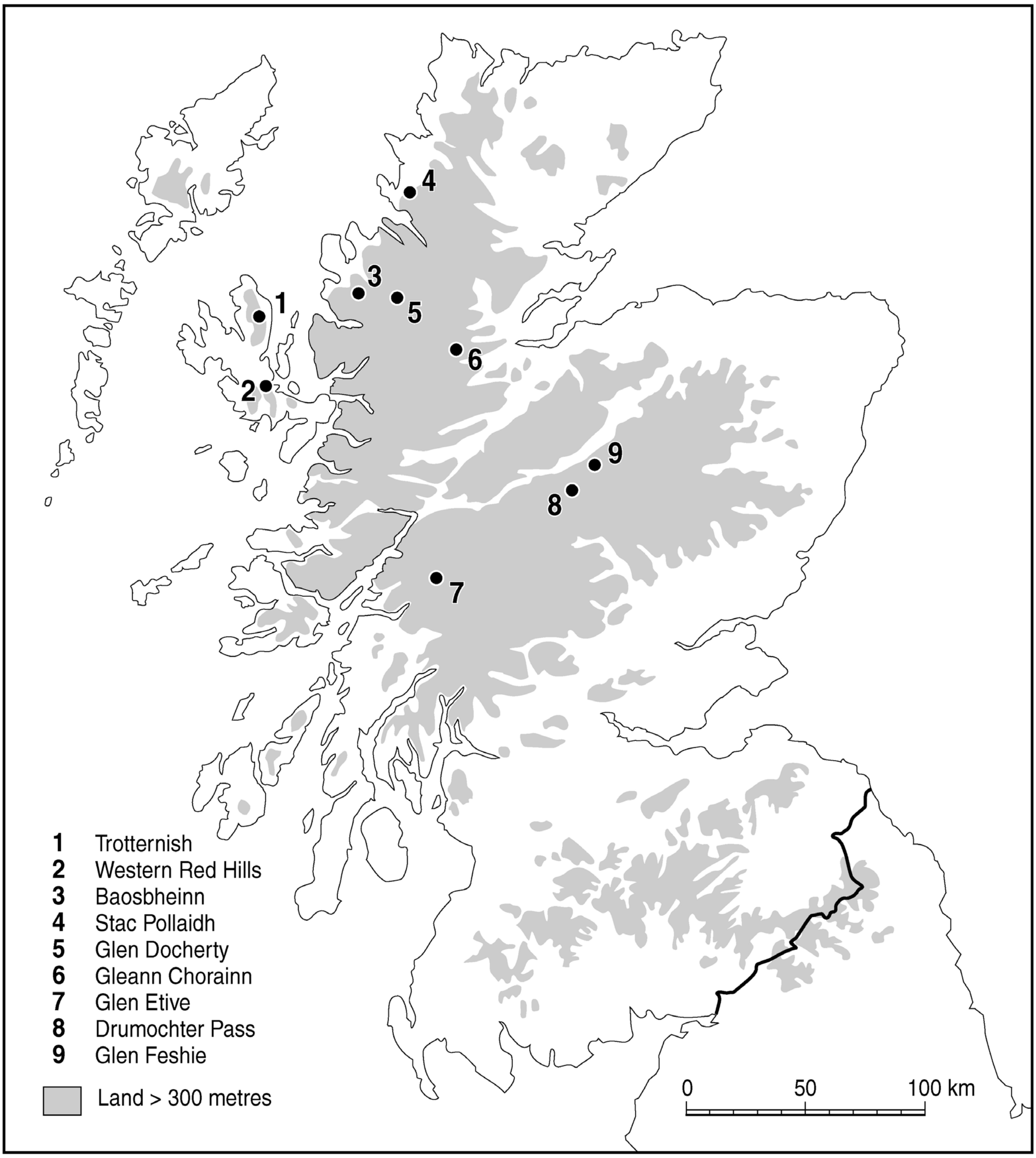
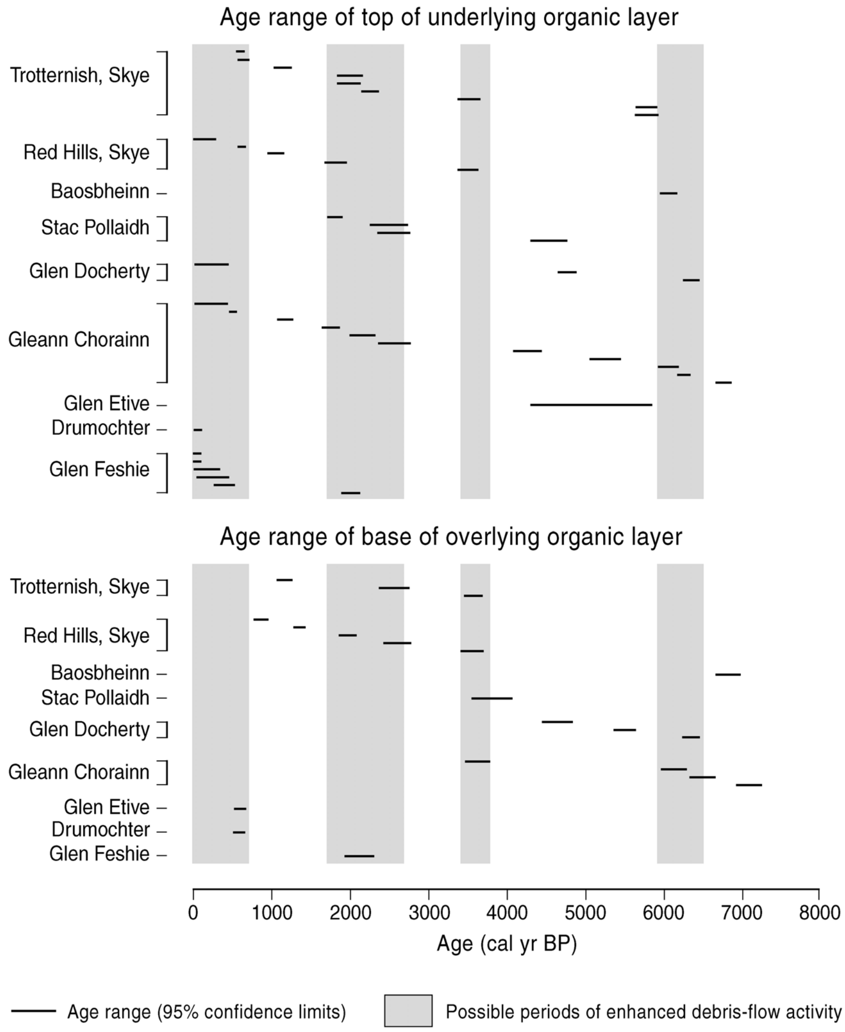


Figure 5 Calibrated radiocarbon age ranges relating to the occurrence of debris flows in the Scottish Highlands over the past 7000 years, showing possible periods of enhanced activity

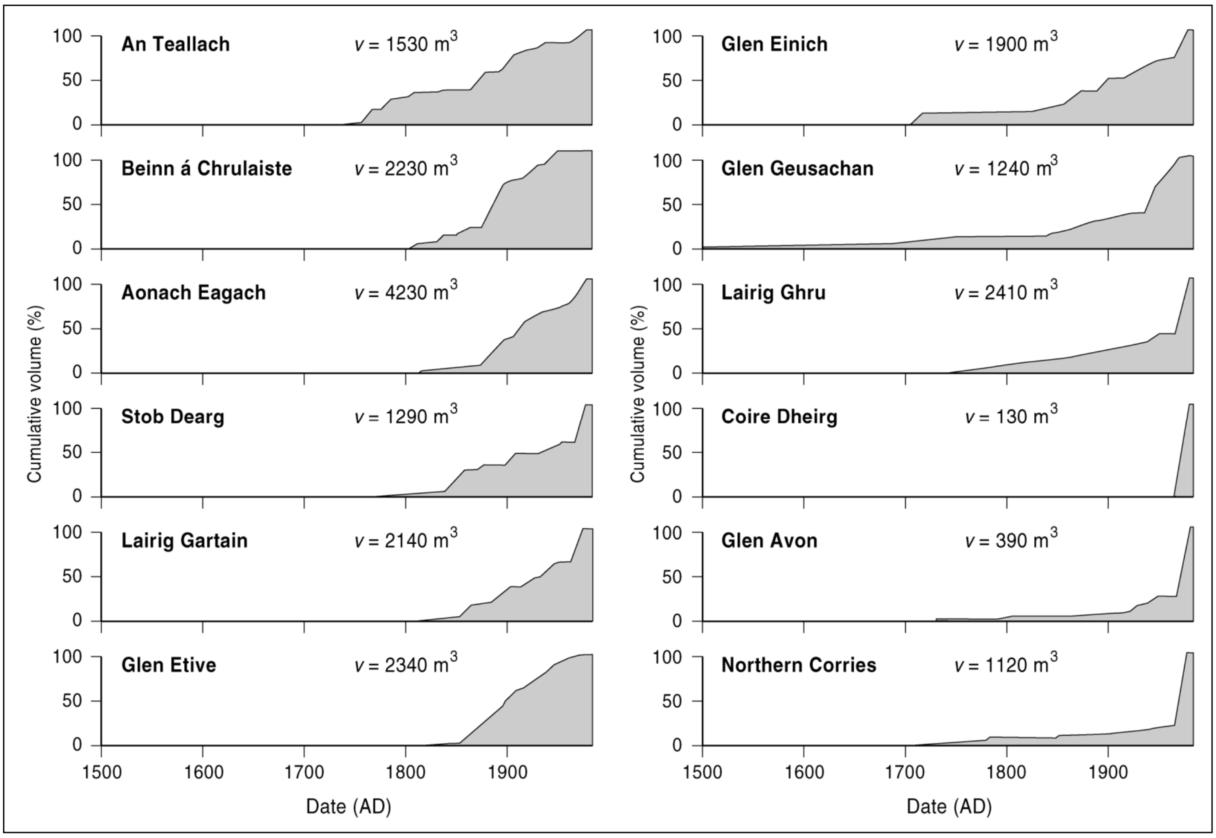


For locations where several debris-flow units have been dated at different exposures, it is possible to calculate an approximate return period for debris-flow occurrence by counting the number of discrete flow units above or between dated organic horizons. As only a subsample of flows have been dated, this approach yields only maximum return periods for particular areas. For five sites on Trotternish, for example, the average return period per site ranges from c. 370 years to c. 900 years, and collectively the 5 sites indicate a maximum return period of c. 150 years for the area. Maximum return periods for other areas calculated in this way are c. 250 years for the Red Hills on Skye and c. 320 years for Glen Docherty. However, these averages conceal changes in debris-flow frequency through time and under-represent (probably markedly) the true frequency of flow occurrence in individual areas. Dates obtained from organic horizons in debris cones where successive flows have spread over the cone surface are liable to be more representative than those obtained from a sample of hillslope flow deposits. Dates obtained from coalescing debris cones in Glen Feshie, for example, suggest that the return period for debris-flow activity over the past c. 150 years is only c. 30–35 years (Brazier and Ballantyne, 1989).

3.2 Lichenometric dating of debris-flow deposits

An alternative approach to dating past debris-flow activity is lichenometry. This procedure involves measuring the diameters of the largest *Rhizocarpon* lichens on debris-flow levées and lobes, then converting these data to age estimates through comparison with a lichen growth curve derived from the maximum diameters of *Rhizocarpon* lichens on dated tombstones in nearby graveyards. Innes (1982, 1983a) employed this approach at 12 sites in three areas of the Highlands (An Teallach, Glencoe-Glen Etive and the Cairngorms). His results (Figure 6) suggested that virtually all debris-flow activity at these sites occurred after AD 1700, with most occurring after AD 1850–1900.

Figure 6 Cumulative volume (v) of sediment transported by debris flows at 12 sites in the Scottish Highlands, AD 1500-1980. The data are derived from dating of exposed flow deposits by lichenometry. From Innes (1983a). (Copyright 2002 © John Wiley & Sons Ltd. Reproduced with permission)



Innes (1982, 1983a) concluded that these data indicate destabilisation of hillslope source areas, possibly by vegetation burning or overgrazing, within the past 200–300 years. This approach suffers from a major drawback, however, in that older flow deposits are liable to be buried by younger deposits (Figure 7), implying a bias towards younger flow ages (Ballantyne, 1987; Luckman, 1992). Moreover, the record of radiocarbon-dated flow deposits (Figure 5) demonstrates abundant debris-flow activity in the Scottish Highlands throughout the past 7000 years, casting doubt on Innes' conclusion that the past 200–300 years have witnessed an exceptional increase in flow activity. Innes (1997) subsequently acknowledged the problem of progressive burial of older flow deposits, but maintained the reality of an increase in debris-flow activity within the past two centuries.

Figure 7 **Recent debris flows in part of the Lairig Ghru, Cairngorm Mountains, in 1961 and 1980, showing widespread burial of an earlier generation of debris-flow deposits by later flows. Adapted from Luckman (1992). (Copyright 2002 © Blackwell Publishing Ltd. Reproduced with permission)**

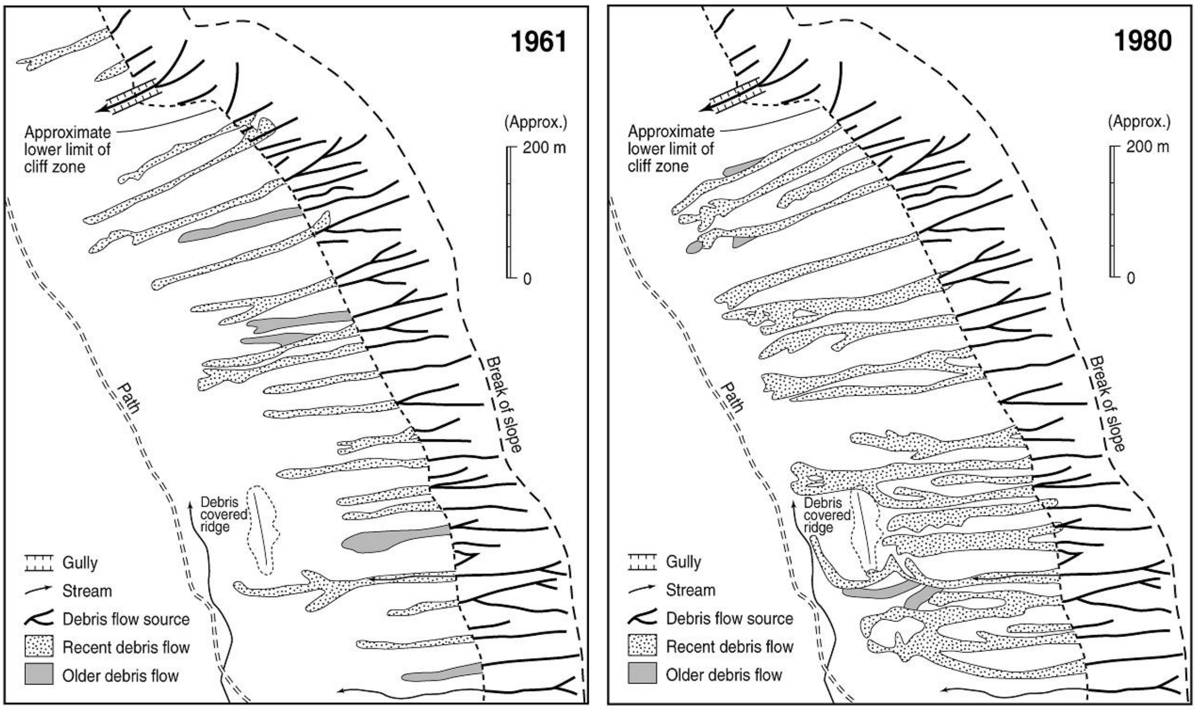
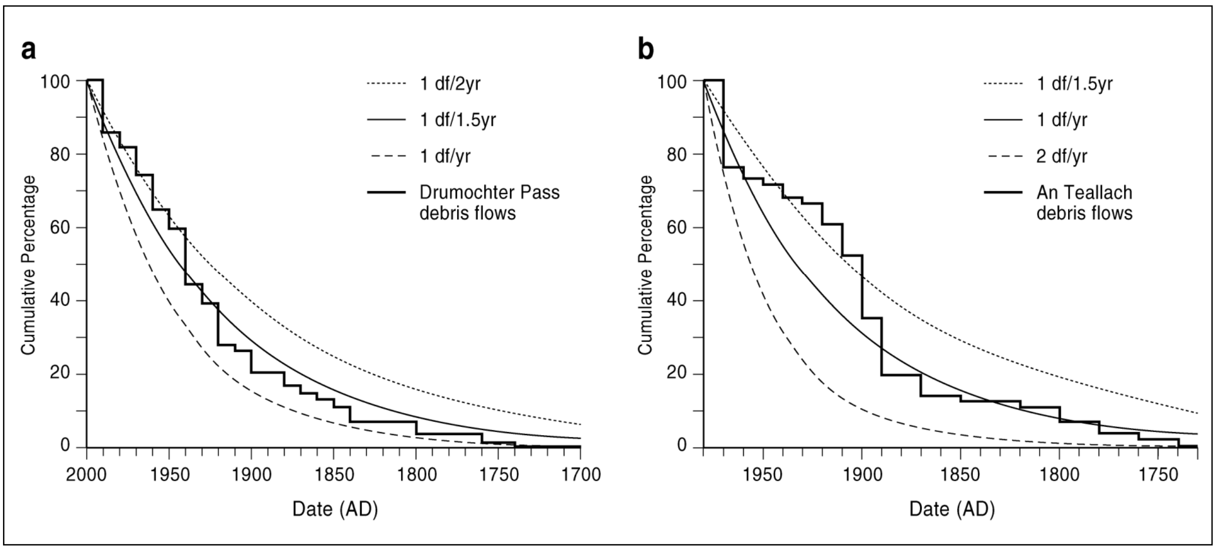


Figure 8 **Cumulative percentage frequency of lichenometrically dated debris-flow ages for Drumochter (left) and An Teallach (right), compared with curves describing the expected cumulative frequency under the assumption of uniform flow periodicity. Adapted from Finlayson (2000) with the author's permission.**



The problem of bias in lichenometric measurements on debris-flows has been assessed by Finlayson (2000), who developed a model for the probability of survival of older debris-flow deposits under the assumption that flow frequency is uniform through time. Finlayson tested this model by measuring the lichenometric age of debris-flow deposits in Drumochter Pass. He showed that the cumulative plot of lichenometric ages is not significantly different from the pattern that might be expected for a uniform debris-flow periodicity of 1 flow per 1.5 years over the past 260 years (Figure 8a), implying that the *apparent* increase in flow activity during this period is probably due entirely to the progressive burial of older debris-flow deposits by younger flows. This form of analysis also allows periods of exceptional activity to be identified. Applied to Innes' data for An Teallach, for example, it shows that there was enhanced debris-flow activity between 1890 and 1920 (when the cumulative frequency of lichenometric ages rises above the 'expected' frequency of 1 flow per year) and again in the 1970s, with a period of relative quiescence between 1920 and 1970 (Figure 8b). Despite the inherent bias in lichenometric dating of debris-flows, the lichenometric data of Innes (1982, 1983b) and Finlayson (2000) provide evidence of a decadal or sub-decadal return period in debris-flow activity on flow-susceptible slopes. At such sites, debris-flow events appear to have occurred in most decades over the past 200 years (Innes, 1997).

3.3 Recent debris-flow events

Recent debris-flow activity was first described in Scotland in accounts of the effects of exceptional rainstorms in Lochaber and Appin in 1953 (Common, 1954) and the Cairngorms in 1956 (Baird and Lewis, 1957). In Lochaber, a convectional thunderstorm on 25 May 1953 resulted in >75mm of rain in 24 hours, with 39mm falling in 2 hours at Fort William and 66mm falling in 7 hours at Kinlochleven. The storm triggered numerous translational slides of till on upper slopes of c. 30°. The resulting debris-flows were channelled down gullies, locally forming debris fans at the slope foot and causing considerable damage to roads, culverts and forestry. In the Cairngorms, a deep depression on 12–14 August 1956 generated 86 mm of rain in 24 hours, and Baird and Lewis (1957) estimated that >150mm fell over the mountains within three days. The storm produced widespread debris-flow activity on the flanks of corries and glacial troughs, stripping up to 13m of till from gully source areas. A further well-documented debris-flow event occurred on the steep southern slopes of the Ochil Hills on 4 November 1984, when 68mm of rain fell in 24 hours (Jenkins *et al*, 1988). Soil moisture conditions were high prior to the storm after an exceptionally wet autumn. This storm resulted in several translational failures of till over bedrock. Individual slides involved 30–359m^3 of sediment, which continued to move downslope as debris-flows.

Though the above accounts represent the only detailed published documentation of recent debris-flows in Scotland, they can be combined with other observations to yield some estimates of the maximum return periods of debris-flow events for particular areas (Table 2). For the Lairig Ghru, for example, Innes (1982) noted fresh debris-flow tracks on 1946 aerial photography, implying a debris-flow event in the preceding decade. Airphotos taken in 1961 show a new set of fresh tracks, which were probably generated by the 1956 storm (Baird and Lewis, 1957). In 1980, Luckman (1992) mapped a further extensive set of fresh tracks, many of which overprint those visible on the 1961 airphotos (Figure 7). These fresh tracks probably represent flows activated by a storm in August 1978, when more than 80mm of rain fell within 24 hours, though some may have occurred in response to storms in 1976 or June 1978. At least 71 individual flows were mobilised in the Lairig Ghru between 1970 and 1978 (Innes, 1983a) but no further debris-flows have occurred in the Lairig Ghru since 1978. In sum, these data suggest that at least three major flow-generating events occurred in the Lairig Ghru between c. 1935 and the present, implying a return period c. 20 years or less.

Table 2 Recent debris-flow generating events in Scotland

Location	Dates (AD)	24h rainfall intensity	Maximum return period	Sources
Lairig Ghru, Cairngorms	Pre-1946 August 1956 August 1978	 86mm/24h >80mm/24h	 c. 20 yr	Baird and Lewis, 1957 Innes, 1982 Luckman, 1992
Lochaber	May 1952 c. 1996	>75mm/24h	 c. 45 yr	Common, 1954 Ballantyne, unpublished
Glen Docherty	1968 1990–1998		 c. 25 yr	Strachan, 1976 Ballantyne, unpublished
Drumochter Pass	1951 July 1978 c. 1990 1995–2000		 10–15 yr	Innes, 1982, 1983a Ballantyne, 1981 Finlayson, 2000 Ballantyne, unpublished
Ochil Hills	Nov 1984	68mm/24h		Jenkins *et al*, 1988
Lomond Hills, Fife	1928 Sept 1985		 c. 70 yr	Ballantyne and Eckford, 1984 Ballantyne, unpublished

Because of the brevity of the observation periods for recent debris-flow activity at the sites identified in Table 2, the return-period data should be regarded as indicative only. They nevertheless suggest that in areas susceptible to debris-flow activity, the recurrence interval of such activity during the past 50 years is at *most* a few decades, consistent with the findings of lichenometric dating.

3.4 Temporal trends: synthesis

The above data allow some conclusions about temporal trends in debris-flow activity. Radiocarbon dating of debris-flow deposits demonstrates at least intermittent activity over the past 7000 years, with some evidence for periods of enhanced activity separated by periods of relative quiescence. Radiocarbon dates for particular areas indicate maximum return periods of c. 150–320 years, but as only a subsample of flows have been dated, the true recurrence intervals were probably much more frequent. The dates also suggest enhanced activity within the past c. 700 years, with an average recurrence interval of 30–35 years over the past 150 years at one site. Lichenometric dating indicates an *apparent* marked increase in activity within the past 200–300 years, but this trend probably reflects sampling bias due to burial of older deposits by subsequent flows. The lichenometric data nontheless provide strong evidence for local recurrence intervals of <10 years to a few decades, consistent with those indicated by airphoto records and direct observations of flow activity over the past 50 years. These conclusions regarding flow recurrence interval accord with those from other mountain environments (Corominas *et al*, 1996, Table 7.3.3).

4 CAUSATION

A critical question posed by the above data is whether or not debris-flow activity has increased in frequency in the past few centuries, and, if so, why. Though the lichenometric data of Innes (1982, 1983a) can no longer be considered reliable evidence of an increased frequency of activity within the past 200–300 years, there is evidence that, locally at least, flow-susceptible slopes are presently more prone to debris-flow activity than at any time since the period of intensive paraglacial sediment reworking that followed deglaciation c. 11,500 years ago. If sites of recent debris-flow activity such as the Lairig Ghru, Glen Docherty and upper Glen Einich (Figures 3 and 7) experienced major debris-flow events every few decades throughout the Holocene, upper-slope sediment sources are likely to have been exhausted within a few centuries or millennia (cf. Ballantyne and Benn, 1994, 1996; Curry, 1999). Sediment sources on such slopes, however, are often largely intact but incised by fresh, active, drift-cut gullies that have acted as the sources of recent flows (Figure 1). The implication is that many such gullies are of relatively recent origin, implying enhanced erosion by debris-flows over a timescale of no more than a few centuries. Similarly, although valley-confined flows often terminate in substantial debris cones that have accumulated over many millennia (Brazier, 1987; Brazier *et al*, 1988; Ballantyne and Brazier, 1989; Curry, 2000b), the accumulated volume of flow deposits in the runout zone of hillslope flows is often very limited, and incompatible with frequent episodes of sediment discharge over several millennia. Innes (1983a) also observed other evidence for a recent increase in activity, such as the burial by debris-flows of abandoned cultivation systems.

The apparent mismatch between the recent frequency of debris-flow activity on hillslopes and the limited volume of sediment eroded from upper slopes and redeposited at the slope foot may be explained in two ways. One possibility is that episodes of enhanced flow activity (such as the present) have been separated by long periods of relative quiescence, as suggested by the clustering of radiocarbon dates obtained for flow activity over the past 7000 years (Figure 5). The other possibility is that the current frequency of debris-flow generation is unprecedented during the Holocene. These two hypotheses are not mutually exclusive.

As noted in the introduction, the primary cause of hillslope debris-flows is a rise in porewater pressures during prolonged rainstorms of exceptional intensity, leading to a reduction in shearing resistance and thus sliding failure and flow. The radiocarbon-dated record of debris-flow events over the last 7000 years (Figure 5) implies that flow-generating storms occurred throughout most or all of this period, and it is unlikely that any marked increase in debris-flow activity over the past few centuries simply reflects an unprecedented increase in the frequency of exceptional storm events. Brazier and Ballantyne (1989), however, suggested that an exceptional storm (or series of such storms) during the 'Little Ice Age' of the 16th–19th centuries AD may have lowered the threshold for subsequent flow initiation by stripping vegetation cover and cutting deep gullies that formed the focus for subsequent flow generation, consistent with a marked increase in hillslope flows over the past few centuries. On a shorter timescale, there is evidence for a general increase in annual precipitation in Scotland in recent decades (Smith, 1995), implying increased ground wetness, which favours an increase in the extent and frequency of debris-flow activity. A similar trend in the incidence of extreme storm events seems likely (A. Werritty, *pers comm*), but is difficult to demonstrate as precipitation records for upland locations are usually based on daily measurements, and thus of insufficient resolution to detect high-intensity rainstorms of lesser duration.

An alternative explanation, at least for hillslope flows, lies in increased susceptibility of soils to initial failure. Modelling of the vulnerability of Scottish hillslopes to shallow sliding failure (Brooks *et al*, 1993, 1995) suggests that progressive pedogenesis (particularly the development of mature podzols) alters the hydraulic transmissivity of soils, rendering failure more likely for a given rainstorm This effect, however, has probably affected steep sediment-mantled slopes progressively over several millennia, and seems unlikely to explain a marked increase in hillslope flows over only the past few centuries. Others have focused attention on anthropogenic causes (Ballantyne, 1991). In Glen Etive, erosion of a debris cone is associated with charcoal deposits and pollen spectra indicating woodland clearance by burning about 500 years ago (Brazier *et al*, 1988). Palaeosols buried by debris-flow deposits at several other sites, however, provide no evidence of prior woodland clearance by burning or otherwise (Brazier and Ballantyne, 1989; Hinchliffe, 1999; Curry, 2000a, 2000b). Innes (1982, 1983a) suggested that burning of heather to improve grazing may have increased the susceptibility of slopes to failure, primarily by destroying the water-absorbing moss cover and thus increasing the likelihood of soil saturation during extreme rainstorms. He noted that in Drumochter Pass, hillslope flows occurred in 1951 within a few weeks of extensive heather burning, and that hillslope flows on Beinn Achaladair near Bridge of Orchy are reputed to have occurred following a fire. Overgrazing by sheep was also considered by Innes (1983a) to be a possible contributory factor.

There are thus several untested explanations for an increased frequency of hillslope debris-flows over the past few centuries. This may reflect natural causes (increased incidence of extreme rainstorms, and/or changes in soil hydrology due to progressive pedogenesis) or human activity (woodland clearance, heather burning or overgrazing), but no single causal factor has been shown to be dominant. However, once initial gully incision has occurred on slopes mantled by a thick sediment cover, the threshold for subsequent flow generation is likely to be reduced, leading to an increased frequency of flow activity that may cease only when gully walls stabilise or the supply of available sediment is exhausted (Brazier *et al*, 1988). Such considerations, however, do not affect valley-confined flows that originate in deep bedrock gullies. The large debris cones at the foot of such gullies have demonstrably accumulated over several millennia (Brazier, 1987; Brazier and Ballantyne, 1989; Curry, 2000b), and the gully sources of such flows are unlikely to have been affected by anthropogenic changes. The limiting factors on flow frequency at such sites are sediment release from gully walls and high-magnitude rainstorms that evacuate the sediment accumulated on gully floors.

5 DEBRIS-FLOW HAZARD

Though most debris-flow activity occurs in remote Highland glens and thus causes, at most, minor structural damage, such as destruction of fencing and culverts and erosion or blocking of estate roads, there are exceptions. Debris-flows triggered by the May 1953 storm in Lochaber and Appin dammed bridges and culverts and closed several arterial roads, causing £130,000 of damage in Argyllshire alone (Common, 1954). Debris flows in Glen Docherty in 1968 blocked culverts and closed the Achnasheen – Kinlochewe road. In November 1984 a 350m^3 debris-flow from a till-mantled slope on the south side of the Ochil Hills inundated a house, causing severe structural damage (Jenkins *et al*, 1988). Railways in slope-foot locations are also vulnerable to debris-flow runout, as occurred on the Tyndrum-Bridge of Orchy pass in 1978.

The distribution of debris-flow activity in Scotland suggests that vulnerable areas tend to be located at the foot of drift-, talus- or regolith-mantled slopes with upper-slope gradients exceeding 30°, or on debris cones or alluvial fans located below steep bedrock gullies. Susceptibility to debris-flow is often indicated by the presence of landforms or sediments diagnostic of earlier flow events, particularly bouldery levées and lobes. Given that (1) debris-flow events are known recur on vulnerable terrain within decades, and (2) that flow runout may follow unpredictable routeways, such terrain is best avoided in engineering planning.

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