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The application of GIS-based binary logistic regression for slope failure susceptibility mapping in the Western Grampian Mountains, Scotland

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Abstract

Slope failure has resulted in significant disruption to the Scottish road network in recent years and failure processes are widely considered to pose a very real risk to both infrastructure and road users. The manifestation of proposed regional climate variations could increase the hazard posed by landslide and debris flow activity within upland environments. It is therefore in the interests of decision makers and land managers to delineate the susceptibility of these areas to failure activity. The availability of accurate and high resolution geophysical data presents an opportunity to conduct a susceptibility analysis of proposed risk areas based on existing sites of failure. It is considered that failure sites are identifiable prior to activity and that events are triggered by external forcing in the form of excessive antecedent precipitation conditions. Binary logistic regression analysis is utilized to identify independent geophysical parameters that have been most associated with instances of past failure events. This technique facilitates the delineation of locations characterized by key parameter conditions most inductive to failure given the occurrence of an external trigger. It is proposed that when exposed to external forcing these locations are most susceptible to failure. To identify these locations is paramount to the successful application of any monitoring and/or preventative strategy.

A Geographical Information System (GIS) is the ideal platform from which to undertake such a susceptibility analysis as it facilitates the precise identification of key independent parameter data associated with recorded instances of existing failure locations. The preparation, storage, extraction and analysis of intrinsic geophysical parameters promotes the development of a consistent modelling approach which can be applied to additional regions in the future.

Keywords: Slope failure, Landslides, Debris flow, Susceptibility, Binary Logistic Regression, GIS, Scotland.

Contents

Introduction

Post glacial Scotland has been subject to widespread slope evolution and reworking processes, the majority of which have had little or no catastrophic effect on the human population. Contemporary society is however highly dependant on a transport network that presents a proven risk when exposed to slope processes within certain geophysical settings. This dependency coupled with the ambiguity of proposed climate change scenarios highlight the potential hazard to the Scottish transport network posed by spatio-temporal variations in slope stability. This was realized most recently in late 2006 and during the summer of 2004 with the occurrence of several debris flows causing significant disruption to the Scottish road and rail networks.

Investigation into slope instability within a Scottish context has traditionally taken the form of landslide/debris flow inventories, attempts to correlate past activity with climate data and qualitative assessments of site specific spatiotemporal control parameters (Ballantyne, 1986; 1991; 1993; Brooks, 1995; 1997; Innes, 1983; 1997; Curry, 2000.). The fundamental focus of this type of investigation has been on understanding which geophysical controls have been responsible for past events on a site by site basis (Ballantyne & Brazier, 1989). Such studies have identified that both intrinsic and extrinsic forcing play key roles in the spatiotemporal distribution of activity, however efforts to substantiate a correlation between activity and specific extrinsic forcing have been largely unsuccessful. This is due to both difficulties in quantifying trigger factors and ambiguity surrounding dating of past activity. In recent years authors have proposed somewhat limited inventories/classifications of slope processes (Jarman, 2006; Innes, 1983) which include small resolution mapping however these were not intended to delineate future susceptibility or hazard, particularly with respect to the road and rail network. Moreover, little research has gone into the quantitative or cartographic representation of intrinsic parameters within a Geographic Information System (GIS) so as to delineate susceptible locations and thus facilitate mitigation planning. This is possibly as a result of difficulties (primarily cost and lack of availability) surrounding data acquisition and limited interest/knowledge out with specific academic or vested interest groups. Furthermore, the concept that climatic change may increase risk and indeed the actual magnitude and/or frequency of hazard events is relatively new and far from widely accepted.

On a national level however, literature on slope geomorphology and risk assessment displays a greater awareness of the hazard presented by climatic variation, slope instability and landslide events with significant research attempting to maximize GIS use within susceptibility mapping and hazard planning. Authors have utilized various heuristic or statistical methods to create susceptibility and hazard maps, particularly in regions that suffer regular disruption and structural damage from slope instability (Deitrich, 1998). It is generally recognised that within a susceptible area certain independent parameters control the spatial and temporal distribution of slope instability, or the dependent variable. In order to implement mitigation measures it is therefore necessary to firstly understand which casual parameters (independent variables) have significantly influenced positive dependent variable occurrences. Such information can subsequently provide the basis for a susceptibility mapping project whereby potential sites of activity may be identified on the grounds of previous event characteristics.

1.1 Research aim

The object of this thesis is to investigate and apply multivariate statistical analysis (specifically logistic regression) within a GIS environment to determine which independent intrinsic variables significantly influence the occurrence of contemporary landslide activity within the study area. Results will be utilized to create a susceptibility map and analysed to assess the viability of utilizing GIS modelling as part of a broader decision support system pertaining to slope instability monitoring, mitigation and indeed planning for natural hazards.

A key aim of this investigation is to assess whether the spatial distribution of recent landslide activity can be quantified purely by intrinsic geophysical and geoecological parameters. It is therefore assumed that the primary extrinsic (temporal) cause of slope failure is increased pore water pressure within the near subsurface due to infiltration of rainfall (Salciarini, 2006; Iverson & Major, 1987; Reid, 1994). Whilst this assumption is open to criticism it is based on sound reasoning based on the nature of the study setting:

- Firstly this is primarily a GIS study; precipitation data is not available at the resolution required for inclusion in the analysis (logistic regression requires a continuous data layer).
- Within the relatively small study area precipitation is likely consistent, therefore negating the use of this variable within logistic regression analysis. Once again, the aim is to investigate the possibility that out with the 'trigger effect' of extreme precipitation events, failure initiation is controlled spatially by intrinsic geophysical factors (gradient, profile and planar curvature, flow accumulation, elevation, aspect and vegetation)

It is therefore an investigation to assess and delineate the spatial influence of intrinsic geophysical parameters on the location of slope failure initiation zones. It is assumed that these parameters will represent areas of susceptibility to future failure events given the occurrence of extrinsic forcing, such as prolonged precipitation and or vegetation change. Results from analysis will be assessed to determine their suitability to delineate areas of susceptibility and potential hazard.

1.2 The implications of slope instability in Scotland

Globally, slope instability accounts for significant damage to infrastructure and in extreme, primarily urban cases has resulted in loss of human life (Hervas, 2003; Gregersen & Sandersen, 1989; Iverson, 2000). Whilst Scotland has not been subject to such catastrophic events there is proven potential for severe disruption to services and/or communications given the effect of a mass movement event within certain localities (Winter *et al*., 2006)

The focus of this study is on the south west Grampian highlands, a region susceptible to classic upland slope processes ranging from essentially harmless soil creep processes to extreme but infrequent rock falls (Jarman, 2006). These events have been subject to significant investigation and from such inventories it is possible to determine areas of established failure activity (Ballantyne, 1986; 1991; 1993; 2002; 2004; Jarman, 2006). Traditionally however, these investigations have not utilized GIS to analyse factors responsible for activity. Elsewhere within Scotland the Rock Slope Hazard Index system (ROSHI), developed by McMillan and Matheson (1997) for the Scottish Executive's use on trunk roads deals only with the risk posed by rock slope failure.

Landslide/debris flow activity is reasonably widespread within the Scottish highlands occurring regularly in high mountain environments where damage to human infrastructure is often minimal. Such activity has therefore gone largely unrecorded out with the interest of geomorphologists. However, due to the geophysical environment that transects Scotland it is unavoidable that transport networks pass through mountain environments and by doing so elevate the risk posed by such slope processes. Numerous landslip events occurred throughout the Scottish highlands during August 2004 resulting in various instances of severe damage and disruption to transport infrastructure.

Figure 1.2. Debris flow activity in Glen Ogle, Perthshire, Scotland 2004. (Copyright Perthshire Picture Agency: www.ppapix.co.uk).

It has been widely accepted that these events were due primarily to the occurrence of extreme precipitation that month, however localized casual factors are considered to have had a key influence on the spatial distribution of events (Winter *et al*., 2006). This period was perceived widely among the public as a one off, disregarding evidence and literature that suggest a widespread increase in related activity during recent centuries (Innes, 1983) and even decades (Wieland *et al.,* 1999). The winter of 2006 saw further cases of disruption within both the rail and road networks as a result of slope instability and flooding, providing further justification for the development of a monitoring programme.

While the manifestation of future climate scenarios remains uncertain and may have a variety of impacts on the landscape, a significant volume of research has focused upon the implications of extreme weather on society particularly within the subject of flood prediction and mitigation (Crooks *et al*., 1996; Prudhomme *et al*., 2002; Reynard *et al*., 2001; Schreider *et al*., 2000). It is proposed that in Scotland and within the UK as a whole winter is the primary flood risk period (Bayliss & Jones, 1993) and that a predicted increase in average winter precipitation could likely result in increased frequency flooding. Furthermore, a change in the seasonal balance of extreme precipitation, which is also predicted by UKCIP02 (Hulme *et al*., 2002) may further increase the occurrence of slope movement processes, particularly if soils are experiencing rapid and significant changes in moisture content. Kay *et al*., 2006 demonstrated that regional climate models (RCM) could be utilized not only to investigate the possible impacts of climate change but to generate a spatially consistent time-series of precipitation across the region of the RCM. Unfortunately RCM data is of too large a spatial resolution to be utilized within a localized study such as this but they will certainly become applicable to broader studies and attributing temporal risk to monitoring systems (Casadei *et al*., 2003). Given the uncertainties surrounding the proposed ramifications of climate change within Scotland it appears that to investigate the key spatial controls on debris flow activity on a local level may facilitate a more effective approach to precipitation monitoring and failure mitigation. Fundamentally, debris flow activity is a geomorphological system and as such "is a structure of interacting processes and landforms that function individually and jointly to form a landscape complex" (Chorley *et al*., 1984).

While it is certainly ambiguous to define the future likelihood and physical location of slope instability, it is equally if not more problematic to define the actual risk that is posed by the susceptibility of certain areas to activity. Moreover to differentiate between susceptibility and risk relative to the road network (defined as hazard) is an issue to be addressed in further detail during section 4 of the report. Such uncertainty has compounded the problem posed by the physical process, for thus far little effort has been made to quantify the susceptibility, hazard or potential risk and to take the necessary steps to put forward and assert a monitoring programme. This lack of action is thought to have resulted primarily because the actual risk to Scottish infrastructure has in the past been considered rather speculative, given that much of the potential for activity is controlled by precipitation events, the future distribution of which is essentially unknown.

Regardless of the localized nature of debris flow activity and the complications involved in predicting the spatio-temporal distribution of occurrence, it is believed that the potential disruption to infrastructure and land use planning within Scotland is significant enough to justify a structured susceptibility assessment and monitoring programme. It is a socio-economic requirement to prevent disruption and damage (Crosta, 2006) and in order to fulfil this it is necessary to identify a method that tackles the problem in the most efficient and effective form. To meet such requirements it is considered that the solution should not only identify the independent factors that lead to susceptibility but facilitate the subsequent monitoring of areas identified as susceptible for factors indicative of failure. It is apparent that GIS is an optimum base from which to tackle this problem, in that it facilitates the consistent identification and modelling of control parameters based on a scientific and methodological data input. Subsequent analysis of information through the GIS ought to promote effective monitoring of susceptible slopes and of subsequent risk.

Unfortunately any form of preventative policy will be an economic burden regardless of methodology and while this investigation looks to identify and monitor susceptible slopes utilizing a modelling approach, expert qualitative assessment is certainly likely to be most effective and is currently in application (pers comm. Transerv uk). However, on a broader scale such a programme requires a consistent, science-based process that is both adaptable to local conditions and replicable over large geographic areas, therefore the benefits of modelling are thought to be worth this investigation. It is however not intended that modelling replace on-site geotechnical investigation, rather that it provides a base from which to apply more effective field/monitoring operations. A model can for example be created rapidly and used in conjunction with qualitative assessment, it can be tuned based on the characteristics of subsequent events and can therefore potentially facilitate more efficient monitoring of conditions. A model or qualitative prediction can only be proved right or wrong by future events and it is arguably more productive to implement a standardized system of prediction and monitoring in susceptible areas so that assumptions can be adapted based on occurrence characteristics. Whilst it is understood that it is not possible, plausible or viable to prevent all slope instability, to not monitor susceptible slopes could potentially result in catastrophic consequences if not severe disruption and cost.

2 The study area

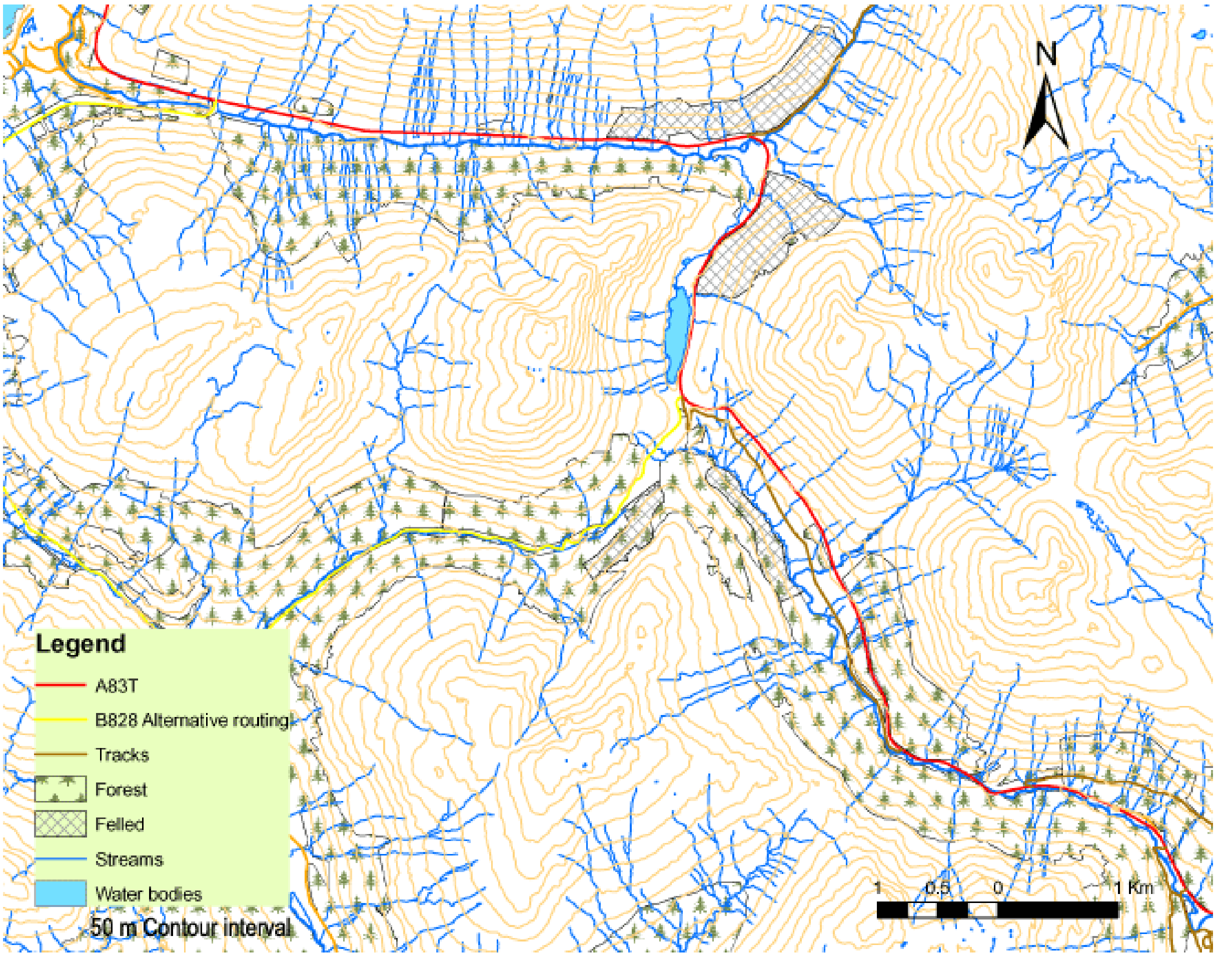


Figure 2. Study area. Crown Copyright original data: Ordinance Survey.

The study area was chosen primarily because it had been considered by the roads operator to be a site of potential landslide risk (pers com. Transerv). It initiates in the south at the head of Loch Long following the divergence of the A83T [trunk] road from the A82T on the shore of Loch Lomond. Leaving sea level the A83T climbs a natural pass through which it is possible to travel between Loch Long and Loch Fye and subsequently beyond, this pass has historically been used as a transport route. The legendary military road builder of the 1700s General Wade took perhaps the first road through the pass, but undoubtedly cattle drovers would have utilized the protection of the glacial valleys in earlier years. Today the A83T is responsible for the carriage of traffic between the south west and the western and central highlands, not only is it therefore a vital logistical pathway in terms of local and regional economics but it provides an accessible leisure route through which to escape the cities of Stirling and Glasgow. The study area focuses on the slopes that bound both the main trunk road and subsequently the B828 that travels east from the rest and be thankful pass (which may be considered the centre point of the study area). The focus ends to the north with Cairndow and is laterally bounded by the slope extension relative to both roads. However, it is prudent to highlight that the main focus shifted rapidly to the A83T when it became apparent that in the event of a road blockage north of the B828 junction, it would be logistically impossible to consider the single track road as a viable diversion option.

Following initial scoping of the study area it is immediately evident that prior to General Wade and the drovers it was ice that considered this to be the easiest route by which to transect the schistose bed rock of the Southern Highland group - the southern most section of the Dalradian block (Dempster *et al*., 2002). The area was shaped by the Late Devensian glacial substage which consisted of three stages: initially the Dimlington Stade of ca. 26-13 ka before present (B.P. [dates before 1950 in thousands of years]), the Late-glacial Interstade of ca. 13-11 ka B.P., and most recently the Loch Lomond (Younger Dryas) Stade of ca. 11-10 ka B.P. (Rose, 1985). The boundary of the Loch Lomond readvance in the south west highlands is not absolutely clear and the vertical extent of ice within certain regions remains highly ambiguous (Ballantyne, 1997; Thorp, 1986). During recent decades the Loch Lomond stade has been the focus of significant research amongst prominent geologists and geographers. Reconstructing the ice sheet extent, the glaciers and resultant climate continues to be a complex puzzle (Ballantyne & Gray, 1984; Gray & Coxon, 1991). A recent study by the British Geological Survey (BGS) (Golledge, 2007) utilized the alignment of former moraines, the distribution of thick till sequences, the altitudes of streamlined cols, glaciotectonic structures and the direction of flow of ice-marginal outwash to model the reconstruction of Younger Dryas palaeo ice flow in a specific area of the western Scottish Highlands. Unfortunately the extent of this reconstruction extends only a few km into the northern boundary of the study area however from the model output it appears that ice reached a maximum vertical extent of 600m within the northern reaches of the study area and perhaps reached only 300m to the south.

Traditionally it has been accepted that due to the underlying massive schist in this region the reconstruction of vertical ice extent by trimlines (perhaps the only certain measure of former ice elevation) is made impossible. This is essentially as a result of the resistance of this Lithology to frost processes, even at elevations known to be well above the ice limits (Ballantyne 1997). Such knowledge of former ice extent is relevant to this contemporary study in that resultant deposition and processes could certainly influence the current susceptibility of areas to slope instability (see Figure 2.1 below). Unfortunately, despite the implication from current literature that the ice did indeed extended from the Ben Nevis massif to cover a considerable proportion of the Scottish Highlands and indeed as far south as Loch Lomond (See fig 2.1 below) it is not possible to delineate exactly the extent (particularly vertically) of the younger dryas ice. It is important to highlight that the younger dryas or locally the loch lomond stade represented a return to full glacial conditions for this region following complete or almost complete deglaciation during the preceding Late-glacial Interstade (Benn, 1997; Sissons, 1979; Thorp, 1986, Golledge, 2006; Hubbard, 1999; Ballantyne, 1989). It is to this re deployment of ice that we owe the nature and distribution of deposits and subsequent paraglacial processes that characterize the region today. The termination of this stade ca 11 ka B.P. as a result of a rapid increase in temperatures (Dansgaard *et al*., 1989) represented a short, sharp return to glacial and periglacial conditions in northern Britain.

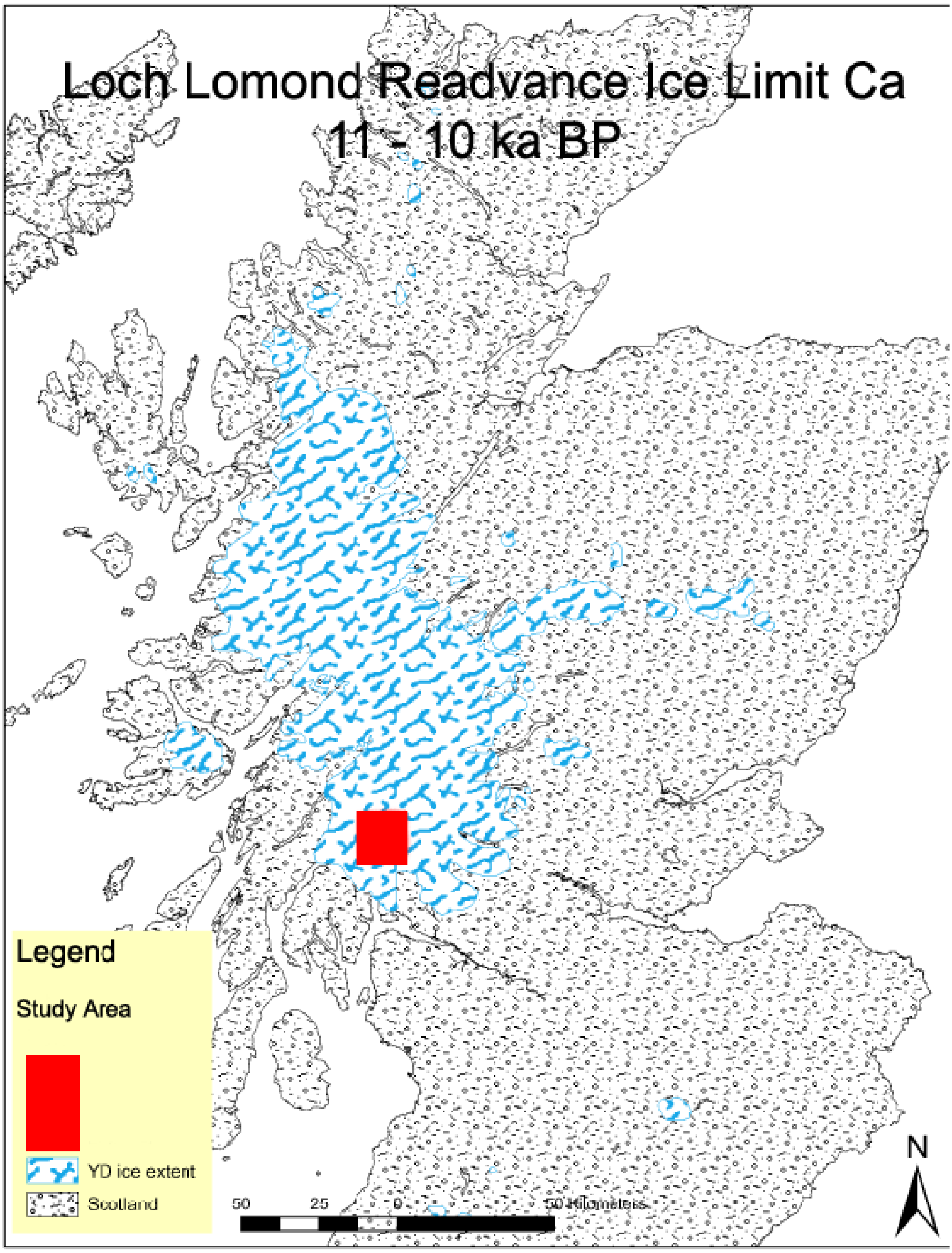


Figure 2.1. The modelled extent of younger dryas ice (Spatial YD ice data obtained from a GIS database developed by Clark *et al.*, 2004)

2.1 Contemporary characteristics of the study area

The regolith mantled slopes of the pass are relatively well stabilized, 10000 years of paraglacial activity has certainly redistributed deposits and it is clear that established scrub vegetation is responsible for this stability. A significant proportion of the valley is forested which has apparently prevented slope instability however significant areas have been felled very recently. Instances of slope failure have taken the form of shallow translational slides or semi-channelized hillslope flow and there are also isolated cases of pervasive and potentially dangerous soil creep. The main A83 (Trunk) road carries up to 5600 vehicles per day and is considered susceptible to disruption as a result of slope instability.

3 Slope failure processes within the study area

In the broadest sense slope failure typically occurs as a result of an extrinsic trigger event compounded by any number of intrinsic independent variables or casual factors which can vary both spatially and temporally, activity is therefore the product of a series of very site specific conditions (Iverson *et al*., 1997). This chapter is focused on the categorization and interpretation of slope processes found within the study area. Landslide is defined by The International Union of Geological Sciences Working Group on Landslides (IUGS WG/L) as "the movement of a mass of rock, earth or debris down a slope" (Cruden, 1991). An objective interpretation of this definition highlights that many geomorphologic processes fit the often generalized term 'landslides' and that there exists no absolute nomenclature to which one may refer when examining failure type. It is therefore necessary to look more specifically at the active processes within the study area whereby the subtle differences in failure initiation have divided activity into hillslope flow and shallow translational slide mechanisms, under the broader term Debris flow.

Out with geotechnical or geomorphology circles slope processes within the study area will likely be referred to as debris flow, mudslide or landslide activity, this section will therefore begin with a review of research literature on core debris flow processes. Debris flows are characterized by intrinsic fluid-like deformation that allows them to display a variety of form and to entrain even boulder-rich debris along existing channels, over relatively gentle slopes and through obstructions (Iverson *et al.,* 1997). Flow viscosity is a result of excessive pore water pressure which leads to material failure and it has been likened to that of dry, flowing sand (Iverson, 1997). Ballantyne (2004) defines *debris-flow* 'as the rapid down slope flow of a debris/water mixture, a term also used in reference 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' (Ballantyne, 2004).

Much of the existing research into debris flow activity in Scotland has focused on established gully flow systems located in more 'extreme' mountain environments relative to the study area. It is considered that such relict reworking localities are essentially a continuation of initial paraglacial activity that began with final deglaciation ca. 11 ka B.P. (Ballantyne, 2002). Despite the age and relict appearance of the lobes many exhibit signs of continued reworking estimated to have occurred since ca. 6.5 ka B.P. to the present. While research has struggled to extract reliable correlation between climate and past activity it is widely believed that extreme rainstorm events perhaps representative of broader climate variations were most likely responsible for cyclic slope reworking during the late Holocene (Brazier and Ballantyne, 1989; Brooks *et al*., 1993; Curry, 2000). The 'little ice age' (approximately 1650 – 1850 AD) is also considered by many to have promoted climatic deterioration in Scotland and hence intensified reworking (Lamb, 1982; Whittington, 1985). It is certainly likely that during the late Holocene and indeed at present, the effects of climate change, extreme climatic events and anthropogenic forcing (Curry, 2000) have and will likely continue to influence the incidence of slope failure, both temporally and spatially. It is perhaps therefore, as a result of recent climatic variations that an increase in slope failure processes and disruption to infrastructure has occurred. However, as emphasised by Curry (2000) the notion that climatic deterioration within Scotland is a certainty or that it shall result in increased upland slope instability can be proven only with time.

In the context of this paper it is necessary to highlight that reworking of relict large scale debris flow lobes generally has little direct impact on society as they occur most frequently in extreme mountain environments and are rarely intersected by infrastructure. Furthermore, flow appears to be regulated both temporally by the availability of up-slope debris and spatially by the very form or nature of lobes (Ballantyne, 1986; Bovis, 1999). Despite the low risk posed by established debris lobes the operational processes and literature pertaining to recent reworking activity is a useful insight into the broader influences on the slope instability processes featured in this analysis. As previously outlined, the study setting is a landscape characterized by deglaciation whose slopes are mantled by till and drift deposits, providing a geophysical environment susceptible to a variety of slope processes. During field investigation it was evident that the area lacked any significant form of aforementioned relict debris flow activity, however certain areas were characterized by vegetated and apparently relict hillslope reworking and contemporary conditions would indicate inherent stability primarily due to a lack of material and established vegetation. In context of the research aim the study will focus on those active processes which have occurred recently (i.e. within a decade) under 'contemporary' climatic conditions (primarily as a result of extreme precipitation events).

3.1 Contemporary slope failure processes

Intrinsic geophysical conditions within the study area are a product of landscape evolution following the departure of glacial ice from the region 10000 ka B.P. Slopes are susceptible to a series of failure processes that have been identified under the broader umbrella of debris flow activity, namely hillslope flow and shallow translational sliding. These have been placed under the broader term of debris flow because hillslope flow is a recognised form of debris flow and because translational slides have been observed to transgress into debris flow as failure progresses down slope. Investigation by the Scottish Executive into the 2004 activity determined that it was primarily flow type events that had occurred throughout Scotland as a result of precipitation conditions (Winter *et al*., 2006). To quantify occurrence based on a single independent parameter such as precipitation conditions is misleading. Precipitation is undoubtedly the ultimate trigger event in the majority of contemporary Scottish slope failures, however considering precipitation is uniform over such a small study area one has to question why flow should manifest itself as different processes and more importantly what has restricted these processes to certain localities, one may argue that the location existed prior to the trigger precipitation event, defined by site specific geophysical conditions.

It is widely accepted (Ballantyne, 2004; Anderson *et al*., 1995) that fundamentally, debris-flows are generated when a build-up of pore water pressure in unconsolidated sediments causes a reduction in shearing resistance. Previous researchers (Johnson, 1984) have concluded that soil would only flow if shear stresses exceed the yield strength (or Coulomb strength), which was conceived to be dependent on slope gradient and soil depth and did not consider variations in pore water pressure. The realization (Anderson & Sitar, 1995; Iverson & LaHusen, 1989) that porosity, pore pressure and subsequent liquefaction were vital components of flow initiation has obviously had significant implications for understanding both spatial and temporal variations in flow. This is supported by established research suggesting that debris flows are caused primarily by infiltration of precipitation (Rapp & Nyberg, 1981; 1988; Rapp, 1987). Furthermore, Brooks (1997) suggests that the less even the distribution of precipitation then the greater the chances of slope failure.

This apparent cause effect relationship is essentially the product of a more complex process that is subject to significant variation based on localized conditions. It has been shown (Findlay, 2003) that slopes can withstand high pore water pressures without failure given that a certain balance of conditions are maintained, this is often a fragile threshold and there are practically any number of unpredictable factors that may either control or perhaps tip the balance and result in failure. This is exemplified by the lack of correlation between precipitation magnitude and flow initiation (Ballantyne, 1989; Curry, 2000; pers obs) in that significant precipitation events need not result in flow if ground conditions at the time can cope with the input. Antecedent moisture conditions are therefore a key determinant of slope stability, prolonged precipitation may render a slope highly vulnerable and the occurrence of a relatively low magnitude precipitation event within that temporal window could result in flow initiation. Drainage boundaries, variations within zone permeability and internal geometry have a cumulative effect on the passage of void water through zones under seepage or consolidation. It is quite likely that slopes in the study area are very resistant to failure, given the established drainage network that has developed since deglaciation, as a form of adaptation to local climate conditions.

Many of the parameters that control pore pressure are difficult to quantify, for example permeability which can be highly dependant on underlying lithology, extent of weathering, drift geology, vegetation cover, drainage pathways, soil desiccation or even animal burrows. Furthermore, the boundaries between fully and partially saturated zones are subject to variations in weather conditions. This has drastic implications for the ideas of susceptibility and hazard within a model output which will be addressed later in a separate section. The findings from the Scottish executive report pointed to key determinants common to flow locations, it is on such grounds that there exists a vested interest in susceptibility mapping of the present study area and it is therefore necessary to further investigate the active failure processes within the study area.

3.1.1 Hillslope flow initiation

The failure activity of 2004 suggests that hillslope debris torrents/avalanches pose a significant hazard to the road network in the Scottish Highlands. Activity is not restricted to any single form and can be considered the product of a variety of preparatory factors and occurrences; these must be outlined in order to understand the operative processes and have been widely investigated within the fields of physical geography and geotechnical engineering. Unlike cyclic reworking of established gully/channel debris cones the location of hillslope debris torrents and flow events are far more complicated to predict, both spatially and temporally (Crosta, 2006; McDonnell, 1990). This was emphasised in December 2006 whereby activity in the study region was apparently located randomly within a broader area of collective (apparent) susceptibility.

Cruden and Varnes (1996) describe hillslope flow as the creation of paths down valley slopes by means of tracks or sheets leading to the deposition of material on lower elevations. Processes that initiate as hillslope flow or torrents can extent to debris flow Slaymaker (1988) events that terminate when flow becomes restricted by a reduction in gradient or similarly where conditions change (while a vegetation change may initiate flow it could also be capable of terminating activity). Slope profile variations can also influence flow intensity, for example a concave slope can promote increased erosion and flow velocity and therefore intensify deposition (Johnson, 2006). Collective basin type slopes will facilitate convergence of gullies which can lead to increased flow magnitude and focused erosion by the primary gully and subsequent increased debris flow (Selby, 1993). In all cases flow is initiated as a result of extreme run off in response to soil/regolith saturation due to prolonged precipitation or when the effect is compounded by a reduction in the capacity of drainage network, due to (for example) excessive debris loading of the channel (Rogers & Selby, 1980; Reid & Iverson, 1992; Reid *et al*., 1988; Johnsson & Sitar, 1990). This is a complex process and dependent on spatial characteristics such as regolith depth and type compounded by vegetation variations as well as slope/drainage parameters which collectively determine pore water pressures.

These scenarios may come about as a result of increased precipitation periodicity and/or intensity brought about by climatic forcing or physically by both changes in vegetation cover and variations in underlying micropores (Cain, 1980). Regarding the study area it is considered from field evidence that capacity is overstretched primarily as a result of prolonged precipitation, although location is dictated by geophysical and geoecological variations as outlined above. Furthermore, the cumulative effect of increased frequency hillslope flow promotes progressive gully development (deepening and widening) which becomes harder to control and could potentially facilitate the transportation of larger volumes of material. This process is evident in the study area. The actual presence of channels and the regulated down slope flow of material and water is not a hazard per se, however the setting can be considered susceptible to risk given prolonged and/or extreme precipitation whereby increased material flow occurs. As outlined earlier with respect to material provenance within established bedrock gullies, a natural threshold will be reached whereby material is exhausted and flow ceases. This is a factor not incorporated into this model but could be a key temporal component of a failure susceptibility monitoring programme.

3.1.2 Translational slide initiation

Relative to flow processes a slide event is defined by a more specific or focused set of conditions in that failure is localized along a consistent slip zone or shearing plane as opposed to the pervasive deformation generally common to flow processes. Sliding can be likened to the incremental movement of material along slip surfaces (Iverson *et al*., 1997), for example a block avalanche. Various contended theories outlining the causation of translational slide events are presented in research literature and uncertainty has been compounded by the influence of site specific variations in geophysical parameters (for an extensive theoretical review of landslides the reader is referred to Iverson *et al*., 1997). In the case of this study the material science within the process is not an applicable parameter, as there is no way it can be incorporated into a data coverage or analysis. Therefore the soil mechanics of slope failure are for the most part out with the scope of this review of slide initiation, which shall attempt to focus on the wider process attributable to attainable geophysical parameters.

As indicated by the nomenclature, a slide implies the presence of a shearing surface and it is this key attribute that differentiates a slide from a flow process (Gregersen & Sandersen, 1989). Initiation of translational slide events is again dependent primarily on prolonged and/or intense precipitation (given the provision of a shear surface) which must be of sufficient severity and duration to facilitate the saturation of the soil/regolith horizon to an extent whereby the water table will reach the surface (Selby, 1993). Individually however, this may not act to initiate movement and for slope failure to occur multiple contributory parameters are required, primarily those which control pore water pressure variations and therefore the stability of the soil/regolith mass above the shear plane. A shearing surface in this context is a boundary between adjacent materials of different properties which therefore exhibit dissimilar reactions to imposed conditions and by doing so result in positive pore water pressures and subsequent instability (Brooks *et al*., 2004)

A prerequisite of failure is that the underlying strata is of reduced permeability and does not facilitate sufficient drainage of soil water resulting in the subjection of the upper layer to a number of stress forces. Acting vertically is gravity and perpendicular to the shearing plane is the normal stress which can be opposed by the uplifting buoyancy effect of increased pore water content. Acting down the slope is shear stress whose opposite force is the shear strength of the soil and put simply, when the shear stress exceeds the shear strength soil becomes extremely susceptible to failure. Shear stress is exceeded as a result of loading due to increased pore water pressures which occur primarily as a result of either prolonged intenseprecipitation, restricted drainage or a combination of both often compounded by increased gravitational forces as a result of high slope gradients, profile curvature variation and vegetation inefficiencies or indeed loss.

It is a complicated task to categorize these geophysical factors by some order of magnitude, as without one another it is likely that the process would not function. In this case precipitation (primarily rainfall and potentially snow melt however the later is less of an issue in Scotland) is again assumed to be the key trigger event and that susceptibility will be graded on intrinsic geophysical parameters which contribute to facilitate sufficient water concentration, excessive shear stress and therefore failure. It is however impossible and indeed perhaps unnecessary to include all of these parameters in the susceptibility analysis as accurate spatial data is not available for all variables. The processes will however be outlined below for the purpose of this review.

Field observations indicate that translational slide initiation zones appear to be rather more clustered than flow events. Certain examples have developed into a flow process particularly given the proximity of an existing channel, this is a recognised occurrence and documented by Iversson (1997). Due to the destabilizing effect of initial sliding, soil remoulding alters the structure (porosity, vegetation, potential infiltration rates) within the vicinity rendering it susceptible to further destabilization. Crozier & Glade (1999) suggest that once an area has been affected by slope instability, it may present a permanent hazard implying progressive activity in these locations. This is likely a result of the decreased vegetation cover within erosion zones which persists long after initial activity due to a very harsh localized ecosystem typified by low nutrient availability, low water transfer capabilities and inherent instability (Flaccus, 1959). Areas displaying evidence of past activity are particularly susceptible because vegetation in mountain settings is slow to regenerate (Rapp, 1976) and it is feasible that within such sites flow can reoccur within decades (Balantyne, 2004).

Field observation highlighted the absolute destruction of established soil structure and vegetation cover following activity, whilst it is likely that displaced root clusters will survive and re-establish rapidly there remains significant areas without vegetation which will be highly susceptible to further (possibly annual) reworking. In this case it was evident that root structure had been limited to the soil/regolith upward of the shearing plane and had not penetrated the till substrate, subsequent saturation and sufficient loading overcame the shearing resistance and given such a scenario, vegetation will not prevent slide. Conversely, it is also conceivable that vegetation could in fact aid flow initiation given saturation as a result of the additional weight (Popescu, 2001). Whilst available vegetation data coverage is not of sufficient resolution to detect changes as a result of previous activity it is evident that soil structure is sufficiently damaged so as to almost certainly increase the susceptibility of these areas. The effect of clustering is not included in the model however it is a process that will likely warrant further investigation within a monitoring strategy.

With respect to both hillslope flow and translational sliding it is possible that progressive pedogenesis may have resulted in decreased shearing resistance within steep drift-mantled slopes and freely drained soils (Brooks 1995). From field observations it appears that this is most applicable to the distribution of shallow translational slides, particularly when compounded by a steeper gradient and underlying till or bedrock. Such a reduction in shearing resistance would increase the vulnerability of the slope to activity given exposure to extreme precipitation events (Brooks *et al*., 1995). However, only when the capacity of the soil to drain is exceeded for so long as to enable significant rise in pore water pressure will the structure lose sufficient strength to fail. This is also dependent on gradient as the greater the gradient the greater the proportion of the force is acting down the slope. On peaty soil this gradient can be somewhat reduced below what may be considered ‘normal’ but these conditions are not met within the study area (Warburton, 2004).The implication of these concepts is that regardless of any actual or inferred climatic variations, hydrological and morphological variations ultimately control the spatial susceptibility of slope to failure.

4 Susceptibility, hazard and risk

Numerous forms of landslide assessment exist within research literature and classifications are often a result of methodologies ranging from simple inventories to heuristic, statistical, and deterministic approaches (Aleotti & Chowdury, 1999; Carrera *et al*., 1995; Dai *et al*., 2002; Deitrich, 1998; Ohlmacher & Davis, 2003; Soeters & Van Westen, 1996). The underlying aim however, is to determine the spatial and/or temporal setting of potential failure given the evaluation of existing instances of activity (Brenning, 2005). Other than a simple inventory the fundamental product of an assessment into the potential spatial distribution of landslide activity is the susceptibility map. This should display both the spatial distribution of existing failures and delineate areas of potential slope failures (Brabb, 1984). Fabbri *et al.,* 2003 highlight that a susceptibility analysis is to effectively apply the law of geological uniformity which is "The past is the key to the future". The underlying assumption of this law is that the processes of the past provide an insight to future processes however this is obviously open to failure given potential excessive variations in extrinsic parameters such as climate and anthropogenic influence which cannot be quantified from previous instances of activity.

Slope instability assessments are primarily conducted if susceptible areas are utilized to some extent by humans and when factors such as infrastructure, the environment, economics or human safety are potentially affected the focus of the assessment may shift (where possible) towards a more quantified delineation of hazard. As outlined above, susceptibility of a slope to landslide implies the possibility of failure in areas where activity has occurred in the past (or those possessing similar properties). When the likelihood of failure is deemed to extend beyond simple possibility the susceptibility analysis can be extended to incorporate a hazard classification which includes the temporal distribution and magnitude of activity. Scheidegger (1994) defines a natural hazard as the probability that a generally stable state may alter rapidly with abrupt effect. A perhaps more established definition is provided by Varnes (1984) as the probability that a potentially damaging phenomenon will occur within a given area and in a given temporal window. Hazard definitions differ from those of susceptibility in that they present information on the timing and the magnitude of predicted landslide activity (Carrara *et al*., 1995; Guzzetti *et al*., 1999) and are subsequently a more qualified basis from which to make decisions on mitigation strategies.

In order to quantify hazard, information is required on the temporal distribution of activity so as to facilitate trend analysis between failure and extrinsic parameter variation (Van Westen, 2003). By including frequency and magnitude (spatial dimension) more emphasis is placed on the expected behaviour of the event as opposed to a purely spatial assessment focused specifically on identifying sites of initiation. Furthermore, in order to effectively determine or quantify hazard it is necessary to model the run out of slope failures so as to delineate the spatial extent and intensity of the hazard at various probability (reaching probability) levels (Crosta *et al*., 2006). This further highlights the difficulty in providing a realistic assessment of hazard for slope instability, because so many unknown variables determine these characteristics. The logistics behind this type of analysis limit significantly the number of studies that have had a valid temporal and/or magnitude aspect (Mulder, 1991), however given the identification of past responses or trends, potential hazard scenarios can be better outlined for the future.

As susceptibility can be deemed a hazard when given a temporal parameter, so hazard becomes a risk when it is considered likely to directly affect the subject of importance

(Remondo *et al*., 2005) or indeed where development encroaches onto areas of susceptibility (Tarolli, 2006). A risk model can be developed by combining a hazard assessment with a map of infrastructure (vulnerability) as outlined by Varnes (1984), such a procedure is complex given variability and uncertainty both within hazard classification and the quantification of vulnerability attributed to infrastructure (or subject). Risk therefore is determined to a large extent by previous damage in the area as a result of activity, in the case of this study area activity physically affected the road in 1999, 2004 (recorded cases from Winter *et al.,* 2006) and is therefore an actual risk. Furthermore, risk can be determined based on the characteristics of the road, in that it increases with the significance and volume of traffic subjected to the hazard. If the road is adequately protected or not potentially subject to susceptibility it can not be at risk. As outlined by Hufschmidt *et al.* (2005) elements at risk and their vulnerability are highly dynamic through time, this is a very important point which can be related back to the fundamental rules of a geomorphological system and is enhanced by natural and anthropogenic influences on the geoecological balance.

This study will focus on susceptibility and having outlined the definitions of susceptibility, hazard and risk it is considered prudent to explain why at best only a broad idea of susceptibility can be generated from this investigation. As a component of landscape evolution, slope failure is dependent fundamentally on intrinsic geophysical parameters including the availability of material compounded by the simultaneous occurrence of destabilising extrinsic conditions and is therefore highly unpredictable. Certain authors (Hufschmidt *et al*., 2005) insist that the occurrence of activity renders the slope a permanent source of hazard, although the nature of erosive processes implies that continued activity will at some point result in exhaustion or some form of steady state. However, the geophysical nature of this very study area highlights that even over a period of 10 000 years the slope continues to evolve therefore one ought to be extremely careful regarding the use of terms such as stable, unstable and susceptible with reference to slope.

The complexity of a chronological dissection of past activity prevents the investigation of key temporal instability processes such as the influence of recharge rates on frequency and magnitude, impact of specific climatic conditions and historical land cover variations. Furthermore, the reconstruction of past activity through multi-proxy evidence such as lichenometric dating, pollen and other palaeo records is rather time consuming, costly and subject to significant confusion/error. This is compounded by difficulties in accurately delineating individual occurrences both spatially and temporally due to reworking and/or incomplete evidence (Ballantyne, 1986). While efforts have been made by various researchers to create chronologies of past activity utilizing multi proxy records, methods are wrought with potential error. Therefore and despite the construction of apparent spatio-temporal relationships, ambiguity concerning temporal accuracy and the identification of initiatory parameters makes anything other than generalized temporal correlation open to justifiable query. Any conclusions therefore, would not provide an adequate foundation from which to make hazard predictions or therefore delineate risk areas.

This study will, then, remain a susceptibility analysis because data capabilities and understanding of climate/failure interactions do not facilitate a ‘worthwhile’ attempt at modelling hazard, and without hazard delineation there can be no effective risk classification. However, it is intended that susceptibility be taken as a base from which to investigate and monitor hazard and risk. In this study the uniformity of fundamental geophysical parameters (and processes) is assumed, as is the significance of extrinsic parameters in failure initiation.

5 Limitations

- Slope failure is clearly distinguishable in the field and on a case by case basis it is certainly feasible to identify which intrinsic controls induce activity, each event is however a localized occurrence characterized by parameters that may or may not be consistent between further instances of activity. Many of the intrinsic geophysical controls on failure susceptibility are inter-related and thus complicate understanding and indeed modelling of the processes involved on a localized basis. Consequently, a susceptibility analysis derived from a 'snap-shot' of the broader process can be criticised on the grounds that conditions inductive to recorded activity were 'a one off'. Furthermore, to delineate susceptibility by modelling reclassified original parameter data could be regarded as a gross generalization.

- It is important to highlight that any prediction of susceptibility will be based on contemporary conditions specific to activity recorded during a field investigation in December 2006 and cannot incorporate response variations as a result of future variations in extrinsic parameter forcing. Moreover, to delineate susceptibility does not quantify slope stability and to label a slope stable or unstable requires significant levels of certainty. Slopes delineated as susceptible to activity by this investigation will fall into the broader spectrum of instability however it is recommended that monitoring and investigation of these susceptible zones be undertaken in order to determine actual stability.

- The acquisition and development of parameter datasets is a lengthy process and can be subject to significant cost if high quality data is to be utilized. Furthermore the collection of dependent variable data is time consuming, arduous and costly. This study incorporates what could be considered the 'basic' or intrinsic parameters derived from digital terrain model (DEM) data. However the study might have included more variables for testing had data been less difficult to acquire. The following variables were not incorporated into the study due to unrealistic cost:

    - Geology data (known to affect failure susceptibility, but is a constant within this small study area)
    - Drift geology data
    - Lithology data
    - Contemporary, high resolution land cover data

- From an economic perspective, to develop an understanding of the frequency, magnitude and spatial extent of failure events requires significant on-going site specific field work which would be hard to justify unless potential risk was conceived to be extremely high. Moreover, temporal investigations are limited somewhat by the lack of, or difficulty in obtaining adequate temporal data pertaining to both records of failure and extrinsic temporal parameters.

6 Foundations of methodology and data requirements

The theory that slope failure is controlled primarily by spatial variations in topography which dictate subsurface flow convergence, increased soil saturation, increased pore pressures and shear strength reduction has been applied regularly within slope instability assessments (Montgomery and Dietrich, 1994). The focus of this analysis is to model susceptibility on intrinsic independent geophysical parameters; those fundamental spatial conditions that are present 'full time' within the study area. An inventory of these parameters extracted from zones of initiation presents a base from which to analyse and model the spatial distribution of susceptibility, on the assumption that extrinsic temporal controls (for example prolonged antecedent precipitation or land cover change) will effectively transform susceptibility into an actual process or indeed hazard. To utilize parameters previously attributed to activity is an established method of susceptibility analysis and is considered an effective means by which to delineate areas for monitoring.

This study will utilize binary logistic regression analysis to model and quantify the effect of independent variable parameters on failure. Put simply, this technique applies maximum likelihood estimation after transforming the dependent variable (slope failure) into a logit variable (the natural log of the odds of the dependent occurring or not) to model the probability of a certain event occurring. It is considered best suited to an investigation of this nature because it facilitates the dichotomous (failure or no failure) classification of the dependant variable (debris flow source area) based on intrinsic geophysical independent variables and the model 'identifies' independent variables most responsible for a positive dependent variable outcome (failure).

The foundation for this methodology is a database incorporating independent variable data attributable to dependent variable location. The extraction of parameter data by dependent variable location is made possible by GIS software and the dataset must include a randomly generated series of points representative of known instances of 'non-failure'. Binary logistic regression analysis requires an equal sample of failure and non-failure dependent variables so as to extract and analyse independent parameter values not attributable to landslide occurrence. This database is a foundation from which to import data into SPSS statistics software for binary logistic regression analysis and from which modelled parameter coefficients can be utilized to generate a susceptibility classification within the GIS environment.

6.1 Database development

The database incorporates geophysical parameters attributable to all existing instances of slope failure in the study area and an equal sample of non failure locations. Therefore a key component of the database is the actual location data of existing slope failure locations within the study area. Prior to undertaking field work it was unclear how prevalent activity would be or what form it may take, however it was known that the study area was considered by the operator of the A83T to be susceptible to failure. Furthermore, during the field survey antecedent conditions had been severe enough to close other roads in the vicinity. The purpose of this database is to organise, store and prepare for analysis independent parameter data that defines the dependent variable. The database therefore includes only data that is both available and considered (based on the literature reviewed in chapter three) to influence the spatial distribution of slope failure.

6.2 Variables

The content of the database is obviously controlled by the distribution of existing activity within the study area and the availability of independent parameter data. The field investigation records all instances of failure and these dictate the number of rows in the database which as outlined above must include an equal number of non-failure locations. The number of columns in the database is governed by those independent spatial parameters which are both available and thought to control the outcome of the dependent variable (the spatial distribution of failure initiation). In the context of GIS modelling the database in this case comprises primarily of continuous parameters (see Figure 6.2.2 below).

6.2.1 Location – the dependent variable

The study area contains what appears objectively to be a negligible proportion of actual failure locations relative to the almost absolute stability displayed throughout the extent of the area. However, hazard has been realized by occurrences of slope failure and the characteristics of these zones are distributed broadly within the region. Therefore one has to consider the resultant wider susceptibility.

General access is made possible within the study area by means of the A83T from which valley slopes ascend and where sites of slope failure are apparent. Fundamental to the methodology utilized in this investigation is the accurate identification and mapping of failure initiation locations, the definition of which confirms to Ballantyne (2004) and incorporates both flow and slide activity (Santacana *et al.*, 2003). Previous investigations of this nature have defined 'location' to be the zone of initiation or failure crown as it is considered to best represent the parameter values which conditioned failure and this study conforms to that rationale. Positional data referring to these zones recorded in Latitude and Longitude by hand held Global Positioning System (GPS) are imported into the GIS and converted to ESRI point shapefile.

As outlined previously a valid binary logistic analysis model of probability requires an equal number of failure and non-failure dependent variables representative of independent parameter values (Koutsias and Karteris, 1998). In order to extract independent parameters pertaining to both failure non failure locations it is necessary to generate an additional random dataset containing a sample of 'non-failure' locations equal in number to actual failure locations. This was created through use of the random points generation tool included in the 'Hawths tools' tool extension to AreView 9.0 which generates a specified number of random sample points within a reference layer (vector or raster) taking care to prevent points from being generated in areas of NoData (there exist some irrelevant areas in the study area whereby flow accumulation calculations have been unable to function resulting in NoData values being attributed to affected cells). It is important to reiterate that all existing (December 2006) locations of activity deemed to meet the aforementioned criteria defining flow or slide activity were recorded within this relatively small study area. This point sample dataset is the a fundamental aspect of a database that can be maintained and modified relative to future instances of activity, variations in slope stability and increased availability or variations in independent data deemed relevant to modelling slope failure. A GIS is considered to be the ideal 'base' for this type of analysis as it facilitates the preparation, extraction and storage of parameter data and subsequently the presentation of findings.

Issues with the location dataset:

- Accuracy of site identification – zone of initiation is taken to be the crown of site failure and was highly evident in each incident of recent activity, particularly with respect to translational slide events. Identification of hillslope flow initiation zones however, created potential for ambiguity as the process can transgress from slide to flow and vice versa. This highlights interpretation of the active processes cannot be 100% objective and may not consider possible unknown relationships between parameters and initiation zone. In this case a direct relation is assumed between dependent variable outcome and active independent parameters.

- A non-failure location absolutely represents a location of non failure during the field study. However due to the random nature of the data it does not imply that any given location defined as non-failure is inherently stable.

- While this study has no temporal aspect and the majority of failure events are undoubtedly very recent, a key assumption is that all recorded activity utilized within this study is a result of contemporary conditions.

- The accuracy of GPS utilized to record location is not considered relevant in this case as error rates fall within the raster resolution of 10 metres which is the maximum cell size present amongst the independent parameter datasets.

6.2.2 Independent variables

Recorded sites representative of the dependent variable are known to be accurate in location however it is equally important that the independent variable data extracted from parameter datasets are accurate. Furthermore they must be in a format that is compatible for entry into binary logistic regression. Figure 6.2.2 outlines the independent variables utilized in the model.

Data layer	**Data type**
Location	*Dichotomous dependent variable (discrete)*
Elevation	Independent variable (continuous)
Aspect	Independent variable (continuous)
Gradient	Independent variable (continuous)
Planar curvature	Independent variable (continuous)
Profile curvature	Independent variable (continuous)
Contributing area	Independent variable (continuous)
Land cover	Independent variable (discrete)

Figure 6.2.2. Database content

All but one of the geophysical variables listed in table 1 (above) are derived from a Digital Elevation Model (DEM); the exception is land cover which is a discrete raster dataset.

6.3 The Digital Elevation Model and independent variables

The development of digital elevation information has had a profound effect on the use and analysis of terrain derivatives within the environmental science, agriculture, geotechnical engineering and hydrological sectors. The simultaneous advances in data capture and GIS analysis capabilities have created a system whereby fundamental parameters key to terrain analysis and land use planning can be generated without leaving the work station. Within surface hydrology where digital elevation data is a valuable tool in the development of flood modelling techniques and pertinent to this study, software developed for terrain and hydrological analysis has generated the potential to derive intrinsic geophysical parameters responsible for debris flow initiation. During the development of data processing capabilities and software, significant volumes of study have outlined the suitability of DEM data for use in geomorphology and hydrology applications (Jenson 1991; Hogg *et al*., 1993; McCormack *et al*., 1993). DEMs are a raster grid or matrix of data where each pixel represents topographic elevation stored in a matrix node (Tarboton *et al*., 2005).

Datasets representing continuous intrinsic geophysical parameters associated with slope failure can be generated through algorithms applied to DEMs. In this study terrain analysis is applied to the Ordinance Survey (OS) Square Grid DEM which is distributed under the name of ‘Landform Profile’ and is interpolated from the contours published on OS 1:10,000 and 1:25,000 scale mapping. The Profile DEM dataset has a resolution of 10 metres and proposes a height accuracy of +/- 5.0 metres in mountain and moorland areas, and +/- 2.5 metres in other areas (Regnauld, 2006). This DEM is of high resolution and quality which is an important control on the accuracy of derived independent parameter data developed within the GIS. However, accuracy can also be influenced by morphological terrain characteristics (Regnauld, 2006). Analysis of DEM data so as to extract terrain parameters generally takes the form of a well documented and standardized process however there exist different algorithms developed by various authors that propose to 'best' perform the calculations.

The standard process is as follows:

- Pit filling corrections
- Computation of slopes and flow direction
- Computation of aspect
- Computation of contributing upslope area
- Computation of curvature

A characteristic of digital elevation data is the presence of artificial 'pits' in the data grid whereby cells or collections of cells are entirely surrounded by cells with a greater value (elevation), this feature may exist in reality within certain glaciated or karst environments and would result in water being unable to flow out of or through the feature. Pits are however often artificial, caused by the occurrence of data errors during elevation sampling or data processing. Pits or depressions are undesirable in a DEM as they will prevent 'drainage' and therefore the function of subsequent flow related algorithms necessary to process derivative parameters from the DEM. A number of algorithms have been written in order to 'fill' pits and ESRI software utilizes a method created by Jenson and Dominique (1988) which raises the depressed values so that they equal the elevation of the lowest pour point on the perimeter of the pit. This facilitates a continuous flow path from every cell to the edge of the data set or the watershed outlet. The creation of a 'depression-less' data set is a routine step in the DEM data analysis and the result is effectively a 'clean sheet' on which to carry out more pertinent analysis. Chapter 6 will progress with a review of each intrinsic geospatial parameter derived from DEM data and outline their influence on failure initiation. Issues concerning the method of acquisition and accuracy will be addressed relative to each parameter.

6.3.1 Elevation

Elevation data is easily extracted from the DEM by a simple procedure utilizing ArcView analysis tools and without the need for further processing. The extracted elevation data relates directly to the dependent variable location point file, each occurrence identifiable by a unique ID number. Literature on the role played by elevation in the initiation of failure regarding the type of activity seen here is sparse. It is an interesting parameter as fundamentally, without elevation there would be no slope and therefore no erosion. Key is to differentiate between elevation, gradient and profile or planar slope, as slope characteristics are widely considered to be the key players in failure initiation. There are however several important direct effects of elevation variation that apparently affect slope stability.

Elevation can determine the severity of localized climate conditions in mountain areas, affecting the spatial distribution of periglacial and earth surface processes as well as key slope stability parameters such as vegetation and rainfall. In the case of established debris flow sites such as those in mentioned in chapter two, elevation induced freeze thaw processes are fundamental to the provision of source material without which flow would not occur. Relevant to the study area and based on field visits it is not clear to what extent freeze thaw processes directly influence failure locations. It is considered likely that severe freeze thaw activity may act to destabilize the upper regolith however this may not coincide with extreme precipitation events which are generally accepted as being the primary cause of failure. Frost heave may however act to 'prepare' or weaken the soil so that it becomes more susceptible to failure given extreme precipitation. Conversely soils in this region are densely vegetated and the established heath land species are highly resistant to both periglacial processes and indeed severe antecedent rainfall conditions. With respect to existing sites of failure it is highly likely that freeze thaw processes prolong and/or induce further activity due to the exposure of bare soil and regolith following the removal of vegetation.

Elevation is known to be responsible for rainfall variations particularly with respect to slope aspect, however this will remain a theory due to lack of precipitation data. Rainfall is also known to increase with elevation and therefore an increase in chemical and physical weathering processes are likely. At this stage prior to analysis it is unclear what role (if any) elevation has on failure activity, and realistically one has to consider that the effect could be so uniform or broadly distributed over an area such as this that it not be detectable through analysis. Moreover it is important to be aware that there is a possibility that colinearity issues may account for apparent elevation/occurrence relationships in that they could possibly be a product of geophysical factors such as flow accumulation, slope profile and particularly the vertical extent of underlying till. Interestingly no instances occurred above 600m, which was considered to be the maximum vertical extent of the Loch Lomond stade ice in this region.

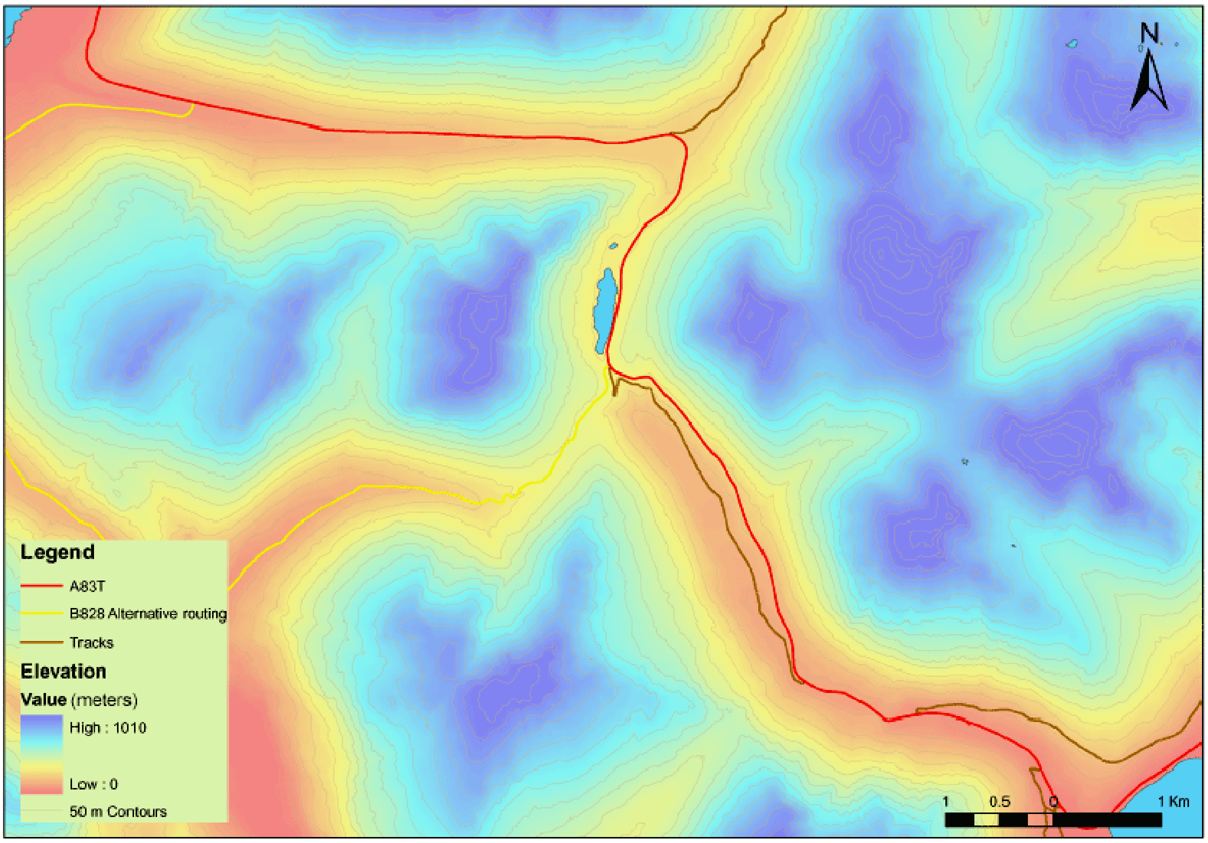


Figure 6.3.1. Elevation raster.

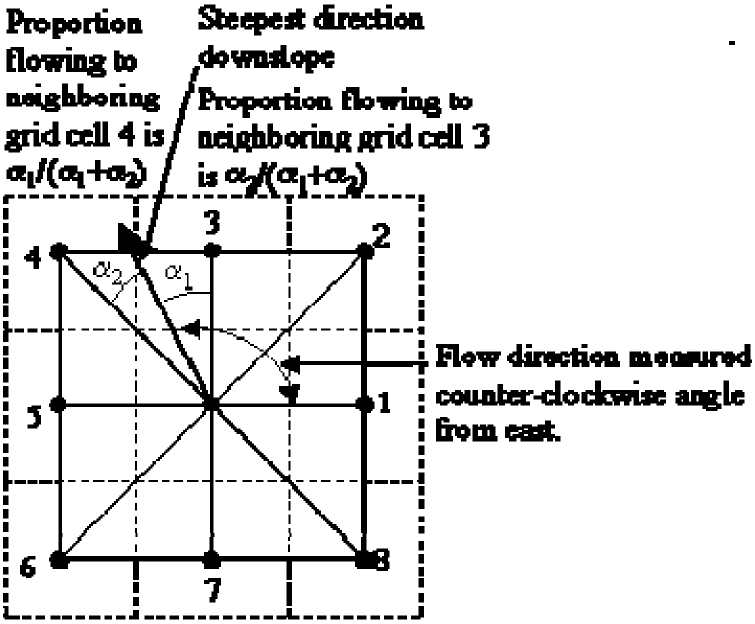
6.3.2 Calculating Flow direction and Gradient

As outlined previously, the DEM raster data provides a base from which to calculate flow direction, slope and subsequently flow accumulation, all of which can be calculated in ArcMap within the hydrology toolbox. Flow algorithms are an important component of hydrological and terrain analysis and are particularly relevant in this case because surface flow is responsible for the concentration of run-off and sub-surface flow which is thought to actively influence slope stability. There are two common types of raster algorithms utilized to calculate either single or multiple flow directions. As suggested by the nomenclature a single flow algorithm facilitates only the passage of flow between single cells whilst multiple flow algorithms incorporate more than one adjacent cell in the distribution of flow (Pilesjö *et al.*, 1998). ArcMap utilizes the D8 algorithm introduced by *O'Callaghan and Mark* (1984) which operates by assigning flow from each pixel to one of its eight neighbours (therefore designated D8 – eight flow directions) either adjacent or diagonal, in the direction with steepest downward slope (Jenson and Dominique, 1988). This method is then a 'single flow' algorithm and while it facilitates simple and efficient data storage within a grid based matrix it results in an over simplified representation of reality (Freeman, 1991). Furthermore, it fails in the level of precision regarding the resolution of flow direction due to the allocation of flow into only one of eight discrete directions (Tarboton, 1997). Subsequently, grid bias can occur due to the orientation of the numerical grid as a result of the coarse flow direction resolution. This can lead to inaccuracies in slope and subsequent flow accumulation (upslope catchment area) calculations.

It is considered advantageous to minimize inaccuracies in data collection, particularly relating to important independent variables such as gradient, aspect and flow accumulation. Various authors have developed alternative techniques comprising multiple flow direction methods (Quinn *et al.,* 1991; Tarboton, 1997), random direction methods (Fairfield and Leymarie, 1991) and grid flow tube methods (Costa-Cabral and Burges, 1994). Tarboton (1997) developed a multiple flow direction method (D∞ or D infinity) which operates by assigning a single flow direction to each cell through the use of a deterministic algorithm that facilitates a more precise resolution of flow direction thus increasing overall accuracy. This method was initially developed in 1997 and an updated version is available within a specialized slope stability mapping tool SINMAP (Stability Index MAPping). This is an ArcGIS plug-in that enables the computation and mapping of slope stability based on geographic information, namely DEM data (Tarboton *et al.,* 2005). The single flow direction (represented as a continuous quantity between 0 and 2π) is determined in the direction of the steepest downwards slope on the eight triangular facets formed in a 3x3 pixel window centred on the pixel of interest (Tarboton,1997).

The method uses a block-centred representation of each elevation value taken to denote the elevation of the centre of the corresponding grid cell. Within the 3x3 pixel window eight planar triangular facets are generated between the centre nodes of each grid cell (as outlined in Figure 6.3.2 below). Every triangle therefore has a 'down slope vector' that when taken from the centre outwards will have an angle that is either within or outside the 45˚ ($\pi/4$ radian) range of the triangle. 'If the slope vector angle is within the facet angle, it represents the steepest flow direction on that facet. If the slope vector angle is outside a facet, the steepest flow direction associated with that facet is taken along the steepest edge. The slope and flow direction associated with the grid cell is taken as the magnitude and direction of the steepest downslope vector from all eight facets'. Tarboton *et al*., 2005)

A.



B.

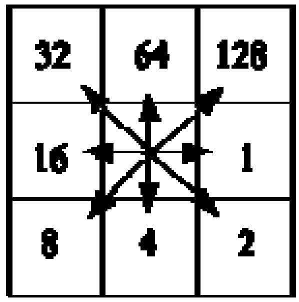


Figure 6.3.2. The D∞ method of assigning flow direction (A. from Tarboton *et al*., 2005) and the D8 method (B. *ESRI*)

Figure 6.3.2 (A) outlines the technique utilized by the D∞ method to measure flow direction counter-clockwise from East as a continuous quantity between 0 and 2π. This angle is determined as the direction of the steepest downward slope on the eight triangular facets formed in a 3 x 3 grid cell window centred on the grid cell of interest (Tarboton *et al*., 2005). The use of triangular facets avoids the approximation involved in fitting a plane and the influence of higher neighbours on down slope flow. Given the scenario where no slope vectors carry a positive value (down slope) the D∞ method sets flow direction by the method introduced by Garbrecht and Martz (1997) which sets flow through flat regions so that they drain towards low ground. This D algorithm is very useful to this to calculate flow direction, slope and subsequent flow accumulation.

Figure 6.3.2 (B) outlines the limitations presented when utilizing the D8 algorithm offered by ESRI ArView software. This allows only eight possible discrete flow directions limited by 45 degree intervals. They are assigned new values as outlined above: North = 64; Northeast = 128; East = 1; Southeast = 2; South = 4; Southwest = 8; West = 16; and Northwest = 32. It is the ability of the D∞ method to assign continuous direction to the slope vector and the distinct failure of the D8 method to achieve this which has led to the selection of the D∞ method for use in this study. Furthermore, the method is utilized within SINMAP to calculate not only flow direction, but also slope and subsequently flow accumulation. This paper is not orientated towards a discussion of flow direction algorithms and the reader is advised to read Tarboton (1997) for a more comprehensive review of flow algorithms.

6.3.3 Gradient

Of key interest to this project is the slope output produced by the SINMAP tools (gradient is **vertical drop/horizontal distance** = tangent of the angle) which can be converted to degrees by taking the Inverse Tangent of the raster, easily achievable through the raster calculator function in the Spatial Analysis toolbox in ArcMap.

Gradient (see figure 6.3.3 below) is a key parameter in any slope stability analysis as slope gradient is widely considered to be a key if not definitive predictor of instability. Regardless of regolith type, underlying geology or antecedent conditions it is gravity and therefore gradient which generate the forces that promote failure. Survey work carried out in the Scottish Highlands by Ballantyne (1981) and Innes (1983) indicate that hillslope flow had been initiated predominantly on slopes with a gradient of 32–42° within a broader range of 30–46° and that slopes with a gradient less than 30° displayed no evidence of flow initiation. Ballantyne (2004) outlines a documented example of a convectional thunderstorm at Lochaber, on 25 May 1953 which saw upwards of 75 mm of rain in 24 hours. Such conditions initiated numerous translational slides on slopes upwards of 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. This is not dissimilar to the activity witnessed at the study area in 2006 and throughout the highlands during 2004. Ballantyne (2004) went on to suggest that the distribution of debris-flows in Scotland is primarily determined by slope gradient.

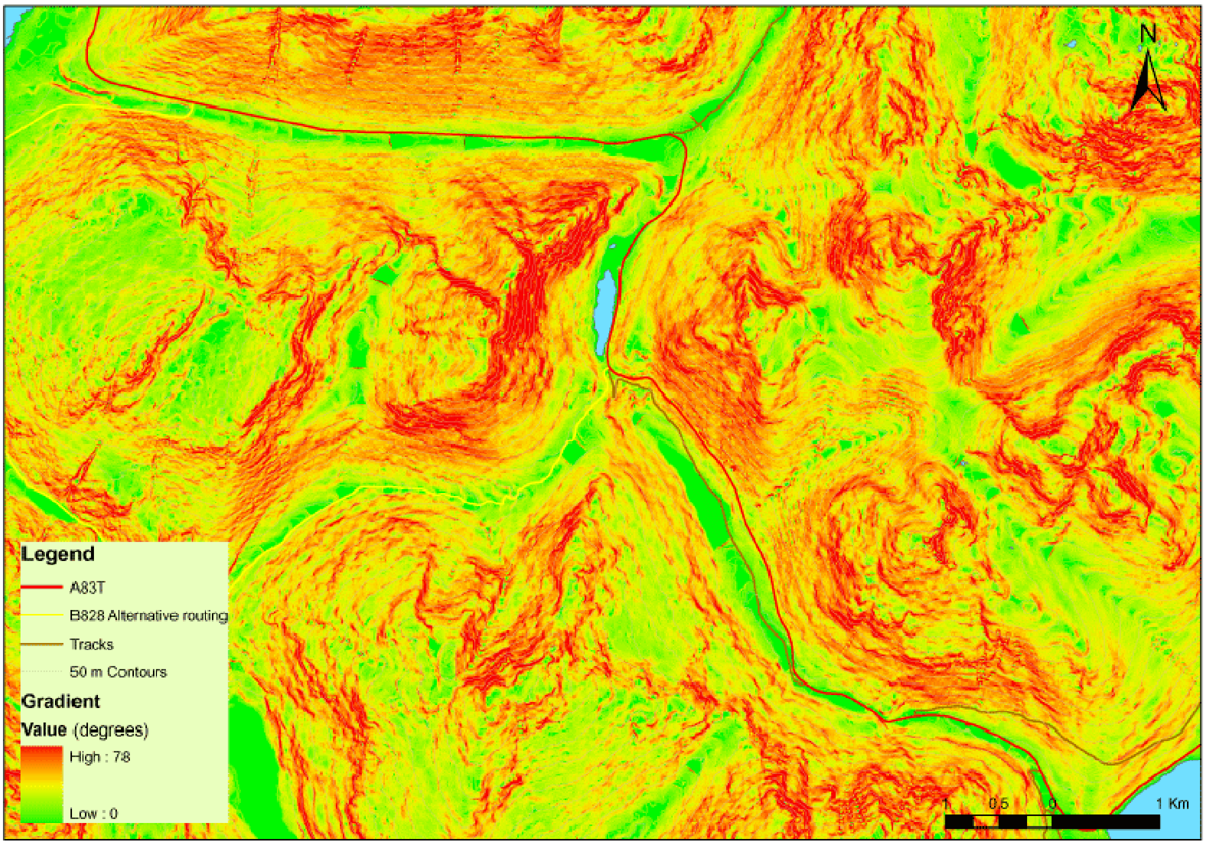


Figure 6.3.3. Gradient generated by SINMAP.

6.3.4 Contributing Area

Contributary area is another derivative of DEM data and has again been calculated using SINMAP, cell values refer to the specific catchment area and represent the number of upslope cells (equating to contributing area). The value is calculated by use of a recursive procedure that is an extension of Marks (1988) highly effective recursive algorithm for single directions (Tarboton *et al*., 2005). 'The upslope area of each grid cell is taken as its own area (one) plus the area from upslope neighbours that have some fraction draining to it. The flow from each cell either all drains to one neighbour, if the angle falls along a cardinal (0, π/2, π, 3 π /2) or diagonal (π /4, 3 π /4, 5 π /4, 7 π /4) direction, or is on an angle falling between the direct angle to two adjacent neighbours. In the latter case the flow is proportioned between these two neighbour pixels according to how close the flow direction angle is to the direct angle to those pixels. Specific catchment area, a, is then upslope area per unit contour length, taken here as the number of cells times grid cell size (cell area divided by cell size)' Tarboton *et al*., 2005).

The procedure was found to have improved accuracy over the D8 algorithm after results were compared to other grid-based methods for calculation of upslope area from grid DEMs (Tarboton, 1997). This outcome was found (on the basis of the evaluation of test statistics and examination of influence and dependence maps) to be true with respect to both low and high resolution test DEM datasets (Tarboton, 1997). It has been demonstrated that contributory watershed area is related to the amount of water that can infiltrate the soil and that a greater catchment area is associated with higher levels of infiltrated water and increased chances of landsliding (Oyagi, 1984). It is encouraging that the data is continuous across the study area and is therefore suitable for the identification and modelling of any relationship that might be identified between upslope flow accumulation potential and failure activity. For this study the number of upslope cells is limited to 1000 as it will only lead to excessive cell counts that apply only to the immediate drainage network and have no affect on slope processes.

Whilst flow accumulation can be modelled from a DEM (see figure 6.3.4 below) it does not necessarily imply that the results are manifested in reality. The actual slope is not subject to the same rules as the cells of a DEM and there are many factors which will influence the flow of precipitation as it reaches the slopes of the study area. Therefore while it is not possible to incorporate precipitation levels into the flow accumulation model it does not detract from the fact that instances of activity may not relate to theoretical calculations of flow accumulation. This parameter has been calculated so that it may be determined through the logistic regression analysis whether this (as any parameter) has a significant effect on the location of positive dependent variable outcomes. Although flow accumulation is directly related to the gradient and curvature of a slope it is in reality more of dynamic variable than it's relatively stable precursor parameters.

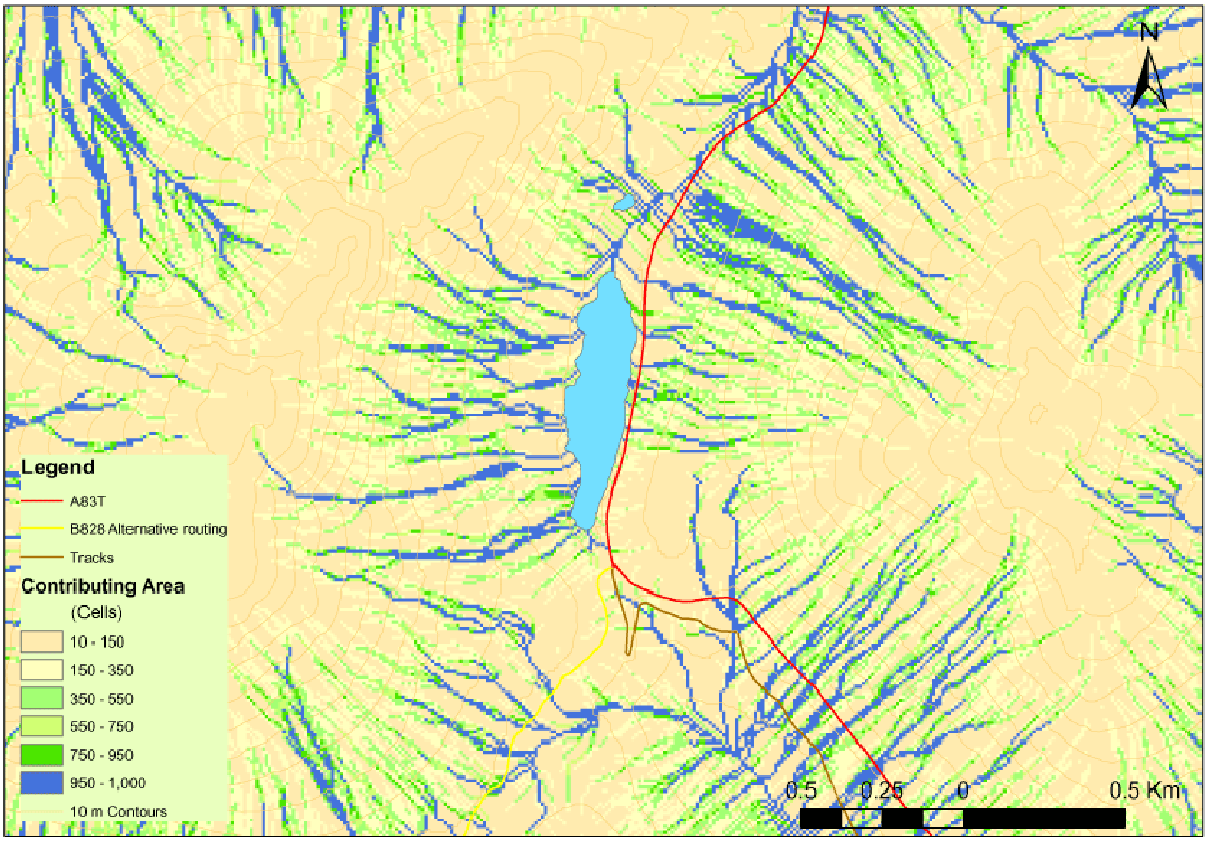


Figure 6.3.4. Contributing area or flow accumulation.

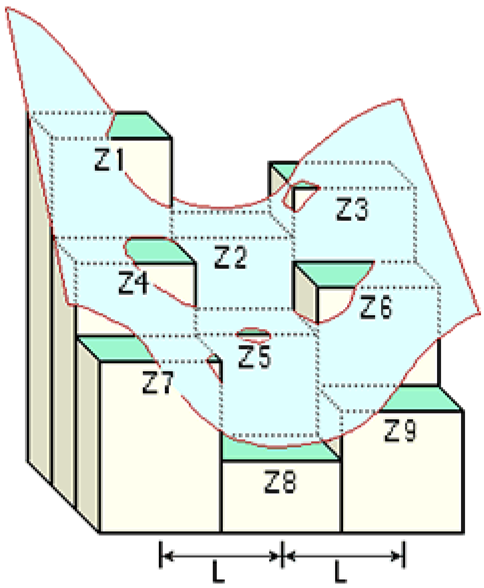
6.3.5 Slope curvature

It is widely accepted that slope gradient controls the rate of flow and that the dynamics of flow are subject to subtleties in slope curvature which can result in the convergence or divergence of flow and therefore respectively intensify or reduce stress. Slope curvature is essentially a measure of the rate of change of slope and takes the form of profile and planimetric (planar) curvature. A slope displaying a concave profile is more likely to promote groundwater convergence towards the base of the slope (Wieczorek, 1987). Convex slopes on the other hand will result in stress zones at the slope crest which could facilitate increased infiltration and potentially an increase in pore water pressures. In this investigation slope curvature is calculated by the Spatial Analyst toolbox in ArcView, from the gradient raster produced by the SINMAP plug-in. The equations utilized within this tool to calculate curvature result in directional derivatives as opposed to the 'true curvature', the directional derivative in this case being the Laplacian of the function defining the surface.

Slope curvature is calculated on a cell-by-cell basis and for each cell in a 3x3 window by a fourth-order polynomial of the form:

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$$

(see Figure 6.3.5 below) when fit to the surface of that 3 x 3 window. The coefficients a through to i are calculated from this surface and the relationship between the coefficients and the nine values of elevation as depicted by Figure 6.3.5 below.




```
A = [(Z1 + Z3 + Z7 + Z9) /4  - (Z2 + Z4 + Z6 + Z8) /2 + Z5] /L4
B = [(Z1 + Z3  - Z7 - Z9) /4  -  (Z2 - Z8) /2] /L3
C = [(-Z1 + Z3 - Z7 + Z9) /4 + (Z4 - Z6)] /2] /L3
D = [(Z4 + Z6) /2 - Z5] /L2
E = [(Z2 + Z8) /2 - Z5] /L2
F = (-Z1 + Z3 + Z7 - Z9) /4L2
G = (-Z4 +Z6) /2L
H = (Z2 - Z8) /2L
I = Z5
```

Figure 6.3.5. Calculating curvature; adapted from ESRI desktop help.

Profile curvature

Profile curvature is the rate of change of slope parallel to slope gradient. Both Profile and Planar curvature are second order terrain derivatives from the original DEM. Profile curvature affects the acceleration and deceleration of flow and, therefore, influences erosion and deposition. The ESRI profile curvature function uses equation (1) below.

$$\text{Profile Curvature} = 2*(DG^2 + EH^2 + FGH)/(G^2 + H^2)*100 \qquad (1)$$

The output grid is the rate of change of slope for each cell. This is the curvature of the surface in the direction of slope (i.e. downslope). A negative value implies that the cell surface is upwardly convex. A positive profile implies that the cell surface is upwardly concave. A value of zero indicates that the surface is flat. Tarboton (1997) has shown that the original 10 metre DEM is of sufficient quality to depict variations in slope curvature that are representative of dispersion and convergence zones which could have implications for erosion.

The output from these calculations is presented below, once again only a proportion of the study area is shown for visual clarity.

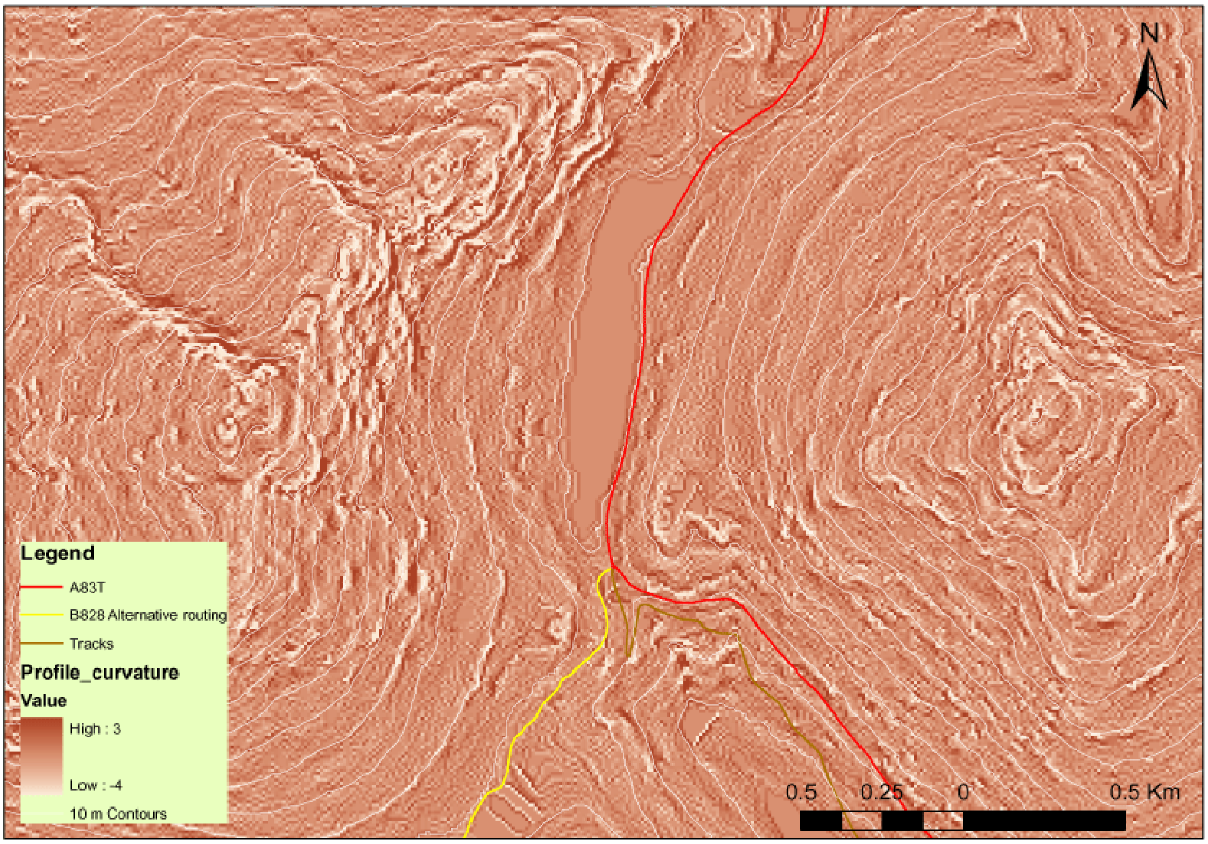


Figure 6.3.5.a. Profile curvature.

Planiform curvature

Planiform (or planar) curvature is the rate of change of slope perpendicular to slope gradient and once more, planar curvature is a second order terrain derivative from the original DEM. The ESRI planar curvature function uses equation (2) below. The planiform curvature influences convergence and divergence of flow, and therefore of relevance to flow initiation.

$$\text{Plan Curvature} = -2*(DH^2 + EG^2 - FGH)/(G^2 + H^2)*100 \qquad (2)$$

A positive cell value implies that the surface is upwardly convex at that cell and a negative cell value implies that the surface is upwardly concave at that cell. A value of zero indicates that the surface is flat (ESRI).

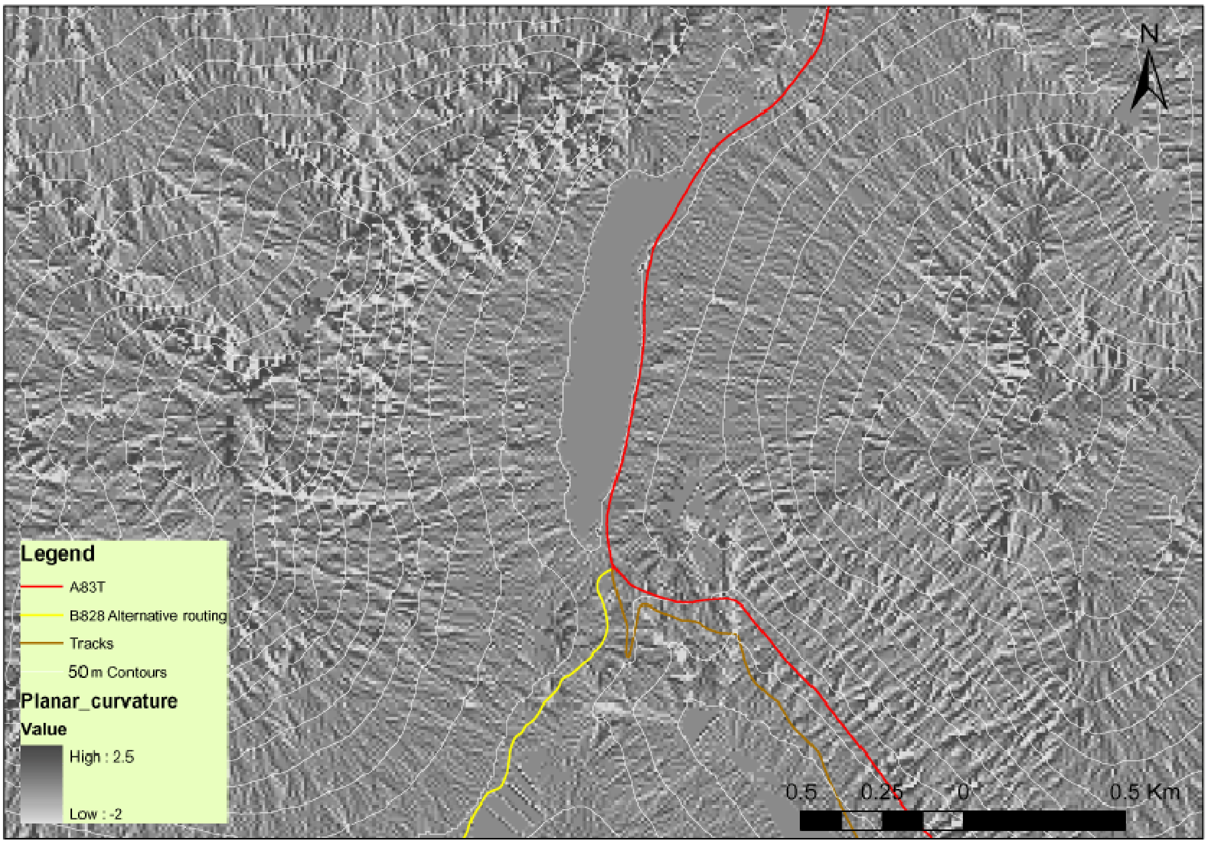


Figure 6.3.5.b Planiform curvature.

Overlaid contours help visualise what is represented by Figure 6.3.5.b and it is especially evident that darker areas represent ridges and lighter areas signify channelling which is of significance in this study as it can concentrate flow and stress.

6.4 Land cover

Land cover, or ecological factors are a key spatial control on activity (Bogart, 2006), asserting a multiple influence on the stability of soil; primarily hydrological (capacity of infiltration into the soil, soil moisture, groundwater level, etc.) and mechanical (root strength) (Greenway, 1987). The land cover data utilized in this study is essentially all that is available without charge or undertaking a site specific classification which given the cost of data coupled with the temporal limitations of this study was unrealistic. The available data then, originates from the 1990 land cover map of Great Britain and was provided by the Centre for Ecology. This data set was produced using supervised maximum likelihood classification of Landsat Thematic Mapper data (Fuller *et al*., 1994). The data has a resolution of 25 meters and accounts for 25 types of land cover, classification accuracy was improved over single image analysis by utilizing both summer and winter images. The resolution of this data is however rather coarse and classification is limited to a minimum mappable size of two pixels, ie 0.125 ha, however it is likely that the actual minimum accurately mappable area is around 1ha in reality. Instances of map error are most probably due to the misclassification of mixed boundary pixels, for example where pixels are adjacent to or intersect a land cover boundary and are thus made up of mixed cover classes. However in the case of this study any error is negligible because at worst case it represents what is a naturally ambiguous boundary between essentially similar mountain vegetation classes. Regarding cover classification accuracy, the realistic land cover map accuracy is thought to be around 80 – 85%. The 1990 land cover classification is displayed below and includes modifications relating to forest areas evident during field work in 2006.

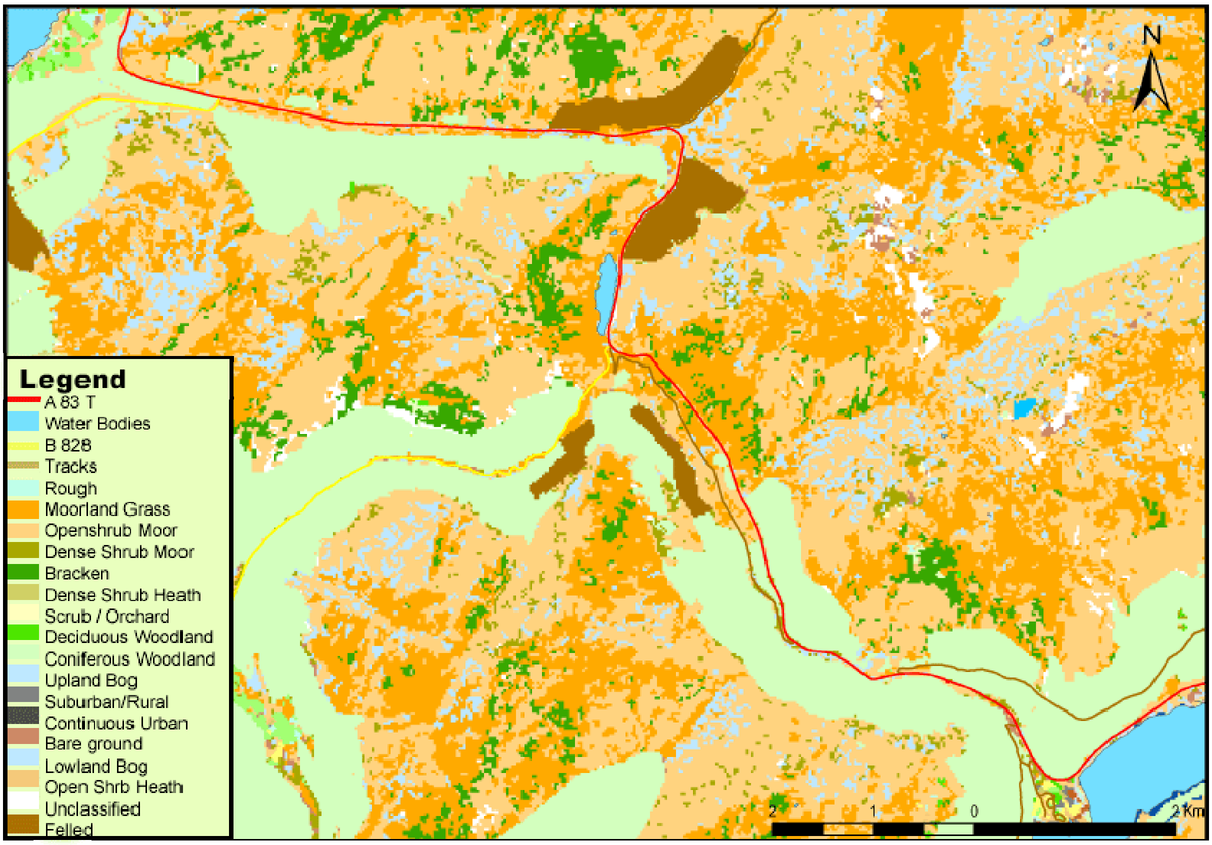


Figure 6.4. 1990 Land cover classification including field revisions by the author in 2006 (original copyright: Centre for ecology and hydrology).

Despite the age of this data set the upland environment that dominates this study area does not appear to have been subject to significant natural land cover changes since 1990. Anthropogenic influences are evident primarily within forested areas and have occurred very recently, it has therefore been possible to record these changes and update the original land cover map. It is difficult to define the actual influence exerted by land cover type on the distribution of failure although it appears that certain land cover types are more susceptible to failure than others (see Figure 6.4.1 below).

Landcover class	**Number of failures present**
Open Shrub Moor	11
Moorland Grass	7
Bracken	6
Dense Shrub Moor	2
Lowland Bog	1

Figure 6.4.1. Distribution of failure within land cover class

This is of course to do with the distribution of classes throughout the whole area, which as outlined by Figure 6.4 (above) is dominated by the three most common classes listed in Figure 6.4.1. However the lack of activity in forested areas is uniform.

7.0 Binary logistic regression analysis

Logistic regression was chosen for this analysis because it is known to be quite flexible relative to alternative methods such as Linear regression modelling which is unsuitable for the dichotomous data utilized in this study as it allows for the dependent variable to take values less than zero and greater than one while a scale of probability can lie only between zero and one. The principle of the Binary logistic regression model is that independent parameter data can be analysed so as to determine which are 'most responsible' for initiating a positive dependent outcome. The significance of the independent variable data therefore affects the output of the model, for example to model many parameters of no great significance produces a meaningless model. The aim is to identify and utilize independent parameters that significantly affect the occurrence of slope failure. The following section is an outline of how the independent variables discussed earlier in chapter five can be assessed so as to identify which influence the dependent variable outcome.

Independent parameter data (x1, x2, x3 ….. xn) are stored in a database relative to the dichotomous dependent sample sites which are equally divided between occurrence (1) and non occurrence (0). Regarding a susceptibility assessment, the inherent benefit of binary logistic regression modelling relative to other multivariate statistical techniques is that predicted values (probability) lie between 0 and 1 (Kleinbaum, 1991). The logistic regression model is a type of generalized linear model that extends the linear regression model by linking the range of real numbers to the 0-1 range (SPSS). It utilizes the independent variables in a linear combination so as to explain the variation in the dependent variable relative to its dichotomous state of failure/non-failure (Dai & Lee, 2003) the purpose of which is to develop the 'best fit' model of the relationship between the dependent variable and the set of independent parameters (Ohlmacher & Davis, 2003).

This output presents a convenient base from which to interpret results and to quantify susceptibility, furthermore it facilitates the modelling of a broad range of parameters as it is feasible to use both continuous and categorical independent variables within the same regression. Unlike linear regression, it is neither necessary that data are normally distributed (dichotomous data have unique distributional assumptions) and it is therefore that logistic regression analysis is utilized as opposed to more common techniques applied to continuous or ordinal data, such as linear regression. Furthermore, logistic regression analysis has a steady history of application within a broad range of subjects and in recent years it has been utilized within several worthwhile publications concerning landslides and slope instability (Dai et al., 2001; Dai & Lee, 2002; Ayalew, 2005).

Consider a continuous variable, Z, which can be thought of as the "propensity towards" the occurrence of slope failure. With respect to landslide susceptibility, Z represents the propensity of a 10x10m data cell to fail, with larger values of Z corresponding to greater probabilities of failure. In the logistic regression model, the relationship between Z and the probability of the event of interest is described by this link function.

$$Z_i = \log\left(\pi_i \,/\, 1-\pi_i\right) \qquad (1)$$

$\mathbf{Z_i}$ = the value of the unobserved continuous variable for the $\boldsymbol{i^{th}}$ case (on the logit scale) and can be calculated by the logistic regression equation (2)

$$\boldsymbol{Z_i} = \mathbf{b^0 + b^1{*}x^1 + b^2{*}x^2 + b^3{*}x^3 + b^3{*}x^3{+}b^4{*}x^4 \ldots\ldots+ b^n {*}x^n} \qquad (2)$$

Where
$\mathbf{b_0}$ is the intercept of the model
n is the number of independent variables or predictors
$\mathbf{b}_{(i-n)}$ is the i^{th} coefficient of the model
$\mathbf{x}_{(i-n)}$ is the x^{th} independent variable or predictor.

$\boldsymbol{\pi_i}$ = the probability the i^{th} case experiences the event of interest

So:

$$\log\left(\pi_i \,/\, 1-\pi_i\right) = \mathbf{b^0 + b^1{*}x^1 + b^2{*}x^2 + b^3{*}x^3 + b^3{*}x^3{+}b^4{*}x^4 \ldots\ldots+ b^n {*}x^n} \qquad (3)$$

Equation (1) can be rewritten to a format suitable for generating a probability output in ArcMap:

$$10^{Z_i} = \pi_i/(1-\pi_i) \qquad (4)$$

$$\pi_i = 10^{Z_i} - (\pi_i {*}\ 10^{Z_i}) \qquad (5)$$

$$10^{Z_i} = \pi_i + (\pi_i {*}\ 10^{Z_i}) \qquad (6)$$

$$10^{Z_i} = \pi_i\,(1+ 10^{Z_i}) \qquad (7)$$

$$\boldsymbol{\pi_i} = \frac{\mathbf{10^{Zi}}}{\mathbf{1+10^{Zi}}} \qquad (8)$$

The coefficients within the logistic regression equation generated by the SPSS (the log-odds units estimated through an iterative maximum likelihood algorithm) for each independent variable are entered into the logistic regression equation within ArcMap. These coefficients provide information on the relationship between the independent variables and the dependent variable. Calculations carried out on the continuous raster datasets produce an output layer that represents $\boldsymbol{Z_i}$ throughout the entire coverage. The raster calculator tool available in

ArcMap includes the base 10 exponential function which allows the calculation of equation (8) which produces an output π_i (probability) for each cell.

In the early stages of analysis it is not clear which parameters have an 'active' influence on the dependent variable, as the logistic regression equation will display good fit statistics and appear to accurately predict dependent variable despite incorporating 'passive' parameters and those that suffer multicolinearity. To determine the significance of parameters it is necessary to 'focus' the equation on parameters that directly influence the outcome of the dependent variable (Ayalew, 2005). These can be identified through interpretation of the significance statistics (the significance of an independent parameter on the dependent outcome) for each of the independent parameters included in the equation (see Figure 7 below)

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1	Contributing_area	.156	5.819	.001	1	.979	1.169
	Gradient	33.475	1.088E3	.001	1	.975	3.453E14
	Profile_curvature	89.522	4.039E3	.000	1	.982	7.567E38
	Planar_cvrvature	-75.816	2.567E3	.001	1	.976	.000
	Elevation	-.540	18.741	.001	1	.977	.583
	Aspect	.249	8.892	.001	1	.978	1.282
	Constant	-594.490	1.919E4	.001	1	.975	.000

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 2	Contributing_area	.006	.004	2.284	1	.131	1.006
	Gradient	.670	.264	6.447	1	.011	1.954
	Profile_curvature	1.925	1.012	3.619	1	.057	6.854
	Planar_cuvature	-1.368	.796	2.955	1	.086	.255
	Constant	-15.745	5.988	6.915	1	.009	.000

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 3	Gradient	.579	.211	7.523	1	.006	1.785
	Profile_curvature	1.606	.767	4.384	1	.036	4.982
	Plan_curvature	-1.264	.690	3.361	1	.047	.282
	Constant	-12.628	4.423	8.153	1	.004	.000

Figure 7. Progressive elimination of independent parameters (Step 1 – 3)

Variables with a significance value greater than 0.05 (See column Sig. in Figure 7) were rejected as not having a significant effect on the outcome of the dependent variable, which in this case is the probability of failure. It was found that removal of parameters not deemed to be significant had a positive effect on the significance value of variables that remained, this is clear from the three steps outlined by the tables above which show how the significance values (Sig.) decrease for relevant independent parameters as insignificant independent parameters are removed from the analysis.

As shown by step 3 above, of all initial parameters offered for analysis it was found that Gradient, Profile curvature and Planar curvature had a significant influence on the outcome of the dependent variable with respect to this data and in this study area. This implies that the remaining independent parameters had no significant influence on the outcome of the dependent variable. The log-odds coefficients (column B above) are used to calculate $\mathbf{Z_i}$ (the value of the unobserved continuous variable for the i^{th} case (on the logit scale)) in the logistic regression equation (2) from above.

$$Z_i = b^0 + b^1 * x^1 + b^2 * x^2 + b^3 * x^3 + b^3 * x^3 + b^4 * x^4 \ldots\ldots + b^n * x^n$$

$$= -12.628 + (0.579*Gradient) + (1.606*Profile\_curvature) + (-1.264*Planar\_curvature)$$

This produces a logit result which can be adjusted to represent probability by use of equation (8) which represents the same logit result as a probability variable (see Figure 7.1).

$$\pi_i = \frac{10^{-12.628 + (0.579*Gradient) + (1.606*Profile\_curvature) + (-1.264*Planar\_curvature)}}{1 + 10^{-12.628 + (0.579*Gradient) + (1.606*Profile\_curvature) + (-1.264*Planar\_curvature)}}$$

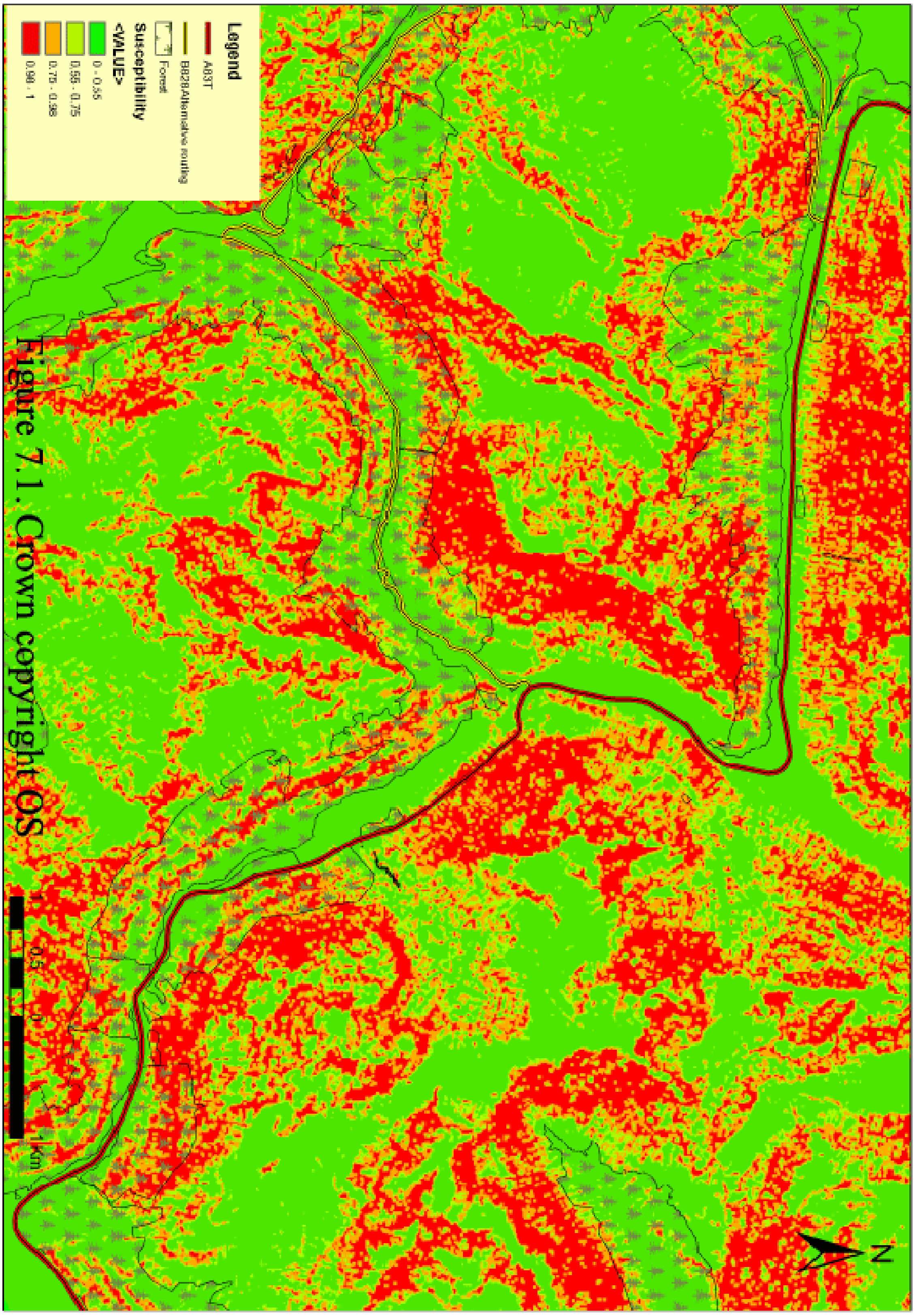


Figure 7.1. Crown copyright OS

8.0 Ranked reclassification

Figure 7.1 (above) represents the broadest possible spectrum of failure generated from significant parameter values which 'could' facilitate slope instability. However this analysis simply implies that a reasonably steep slope has a relatively high likelihood of instability. Such a generalized result is of limited use within this application. On further consideration of the independent parameter data it is evident that a disproportionate number of cells have been assigned a high probability of generating a positive dependent variable because of the broad distribution of values associated with failure. Consider the small dependent sample size (representative of all instances of activity in the study area) and the breadth of variation within independent parameter values. The independent parameter gradient has been used as an annotated example in Figure 8.0 below. This graph displays both gradient values representative of the non occurrence (0) sample and instances of occurrence (1). It is immediately clear that gradient values differ between occurrence and non occurrence but more importantly it highlights that within the instances of occurrence are most prominent within a 'focused' subset of the entire gradient range.

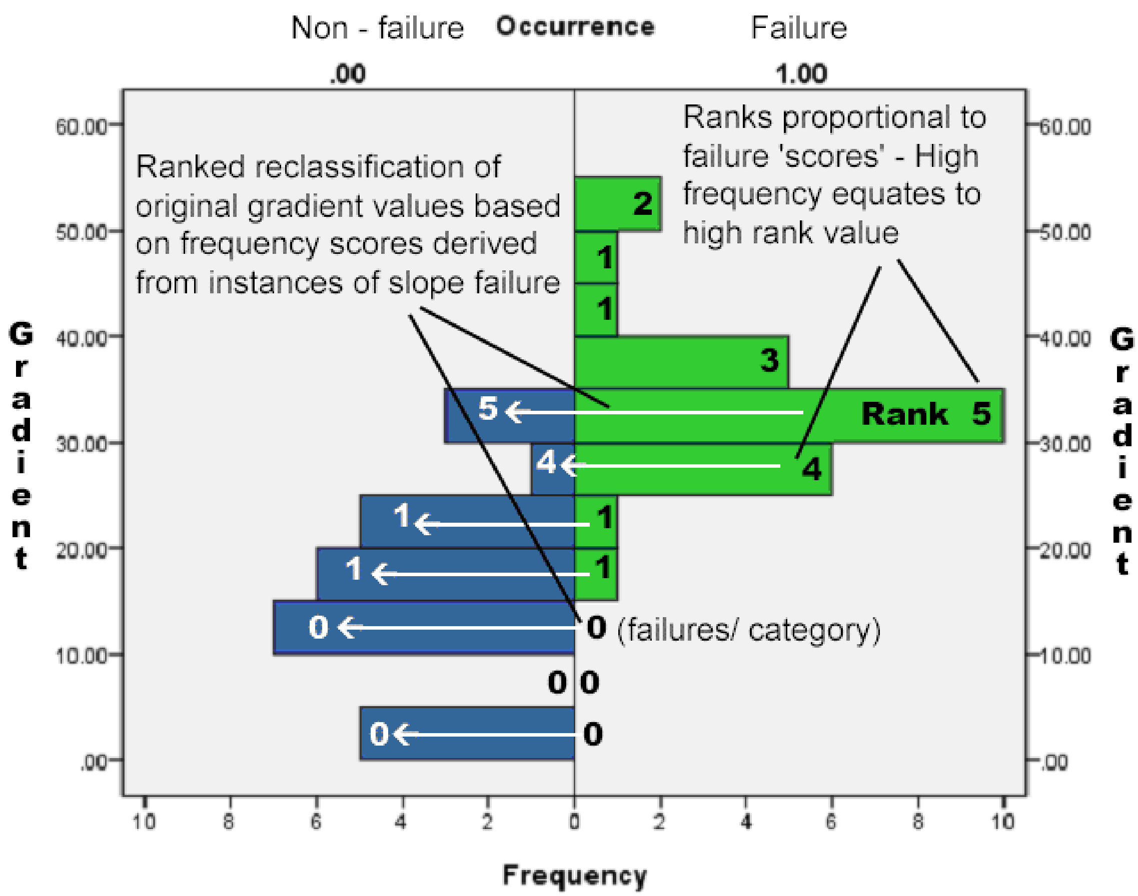


Figure 8.0. Reclassification of original parameter values to ranks based on frequency

The entire gradient rage of 15 – 60 represents a positive dependent outcome but does not 'focus' on the key values. The actual distribution of failure frequency highlights that failure occurs most often within a gradient between 25 and 40 degrees, a range where 21 of the 27 failures have occurred. The method outlined in Figure 8.0 (above) reclassifies original independent parameter data so that it is representative of failure frequency per value category on a ranked score basis. The gradient category with the greatest frequency of occurrence is reclassified with the highest score and categories of gradient that have had not been subject to failure are reclassified as zero. Ranking the variable categories based on frequency will amplify the discrepancy between data values pertinent to the two dependent outcomes (failure or non-failure). The binary logistic regression analysis will 'pick up' on this and model independent parameter coefficients that when applied to the entire reclassified data layers will emphasize the discrepancy and prevent the generalization caused by modelling original data values. It basically reduces the impact independent data least associated with failure can have on the outcome.

Slope Category	Frequency of occurrence	'Rank'
0-5	0	0
5-10	0	0
10-15	0	0
15-20	1	1
20-25	1	1
25-30	6	4
30-35	10	5
35-40	5	3
40-45	1	1
45-50	1	1
50-55	2	2
55-60	0	0
60-65	0	0

Figure 8.1. An example of the ranked classification of categorized gradient values in order to highlight the role of 'relevant' parameter values.

As outlined in Figure 8.1 a gradient of between 30 and 35 is most representative of a positive dependent variable outcome and is therefore assigned the highest rank, this rank decreases in order with each reduction of frequency and values not representative of positive dependent value are ranked zero. Categories that are attributable to an equal number of failures are given an equal rank. The final ranking can be applied to the original parameter dataset by utilizing the raster reclass tool in ArcMap. This method is applied to all original independent variable datasets and the rankings are displayed in Figure 8.2 below.

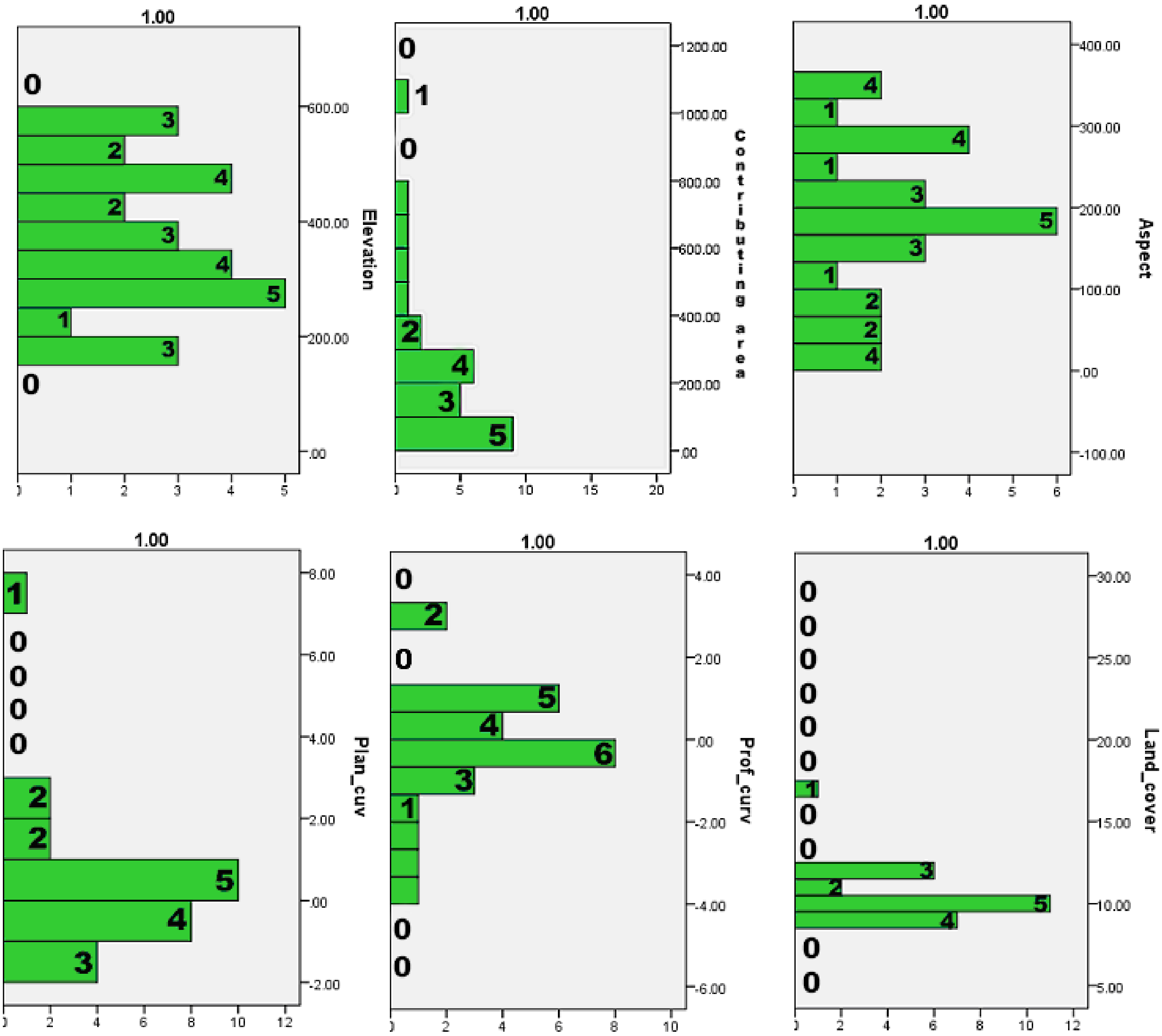


Figure 8.2. Depicts the score based ranks given to each categorized independent variable.

The ranking method explained earlier for the parameter gradient is applied to all independent parameters (See Figure 8.2 above). In order to generate a more focused output the independent parameter values are 'adjusted' so as to be representative of the 'order of importance' carried by individual value categories in their contribution towards a positive dependent outcome. Each set of independent parameter values were categorized and each category ranked to generate a simplified continuous data layer representing the variable on an score proportional to the influence each category exerted on the occurrence of a positive dependent variable.

This method results in continuous independent variable datasets that focus on areas representative of those original value categories most responsible for the high failure frequency. These datasets are subjected to the same methodology as the 'original' values as outlined in chapter 6 (utilizing exactly the same location data as in the extraction of the original parameter data). The aim of the analysis remains the same however the reclassification has filtered out the weight carried by areas representative of original parameter values that had the least effect on failure occurrence. The reclassified ranked data highlights the spatial distribution of values that are known from failure/frequency relationships to have a prominent role in slope failure. This again is based on the 'past is the key to the future' theory.

The reclassified ranked values are not a proportional measure i.e a higher rank does not mean a higher parameter value (eg higher elevation). Ranks facilitate the continuous spatial representation of independent data on a scale relative to the effect original parameter values have on existing failure frequency, so that they bear relationship to what is 'happening on the ground'. It is a focused reclassification of the original dataset, so that the relationships are not dissolved over a broad range of values. As outlined by Figure 8.3 below, when applied to the reclassified ranked datasets the logistic regression analysis identifies the same significant independent variables as those from the original data.

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1[a]	Ranked Gradient	1.145	.291	15.433	1	.000	3.143
	Ranked Profile curvature	.888	.346	6.591	1	.010	2.430
	Ranked Planar curvature	.815	.359	5.150	1	.023	2.259
	Constant	-6.922	1.959	12.481	1	.000	.001

Figure 8.3. Reclassified parameter variables

The ranked reclassification of slope, planar curvature and profile curvature were included in the model.

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	40.655	3	.000
	Block	40.655	3	.000
	Model	40.655	3	.000

Figure 8.4.

Figure 8.4 displays the chi-square statistic and its significance level for the model utilizing reclassified ranked data. Statistics for Step, Model and Block are the same because stepwise logistic regression or blocking was not used. The column Sig. stands for the probability of obtaining the chi-square statistic given that the null hypothesis is true, this is known as the p-value, which is compared to a critical value for example .05 or .01 to determine if the overall model is statistically significant. This is the probability of obtaining this chi-square statistic (40.655) if the independent variables listed in Figure 8.5 (above) have no effect on the dependent variable. The model is statistically significant because the p-value is less than .000.

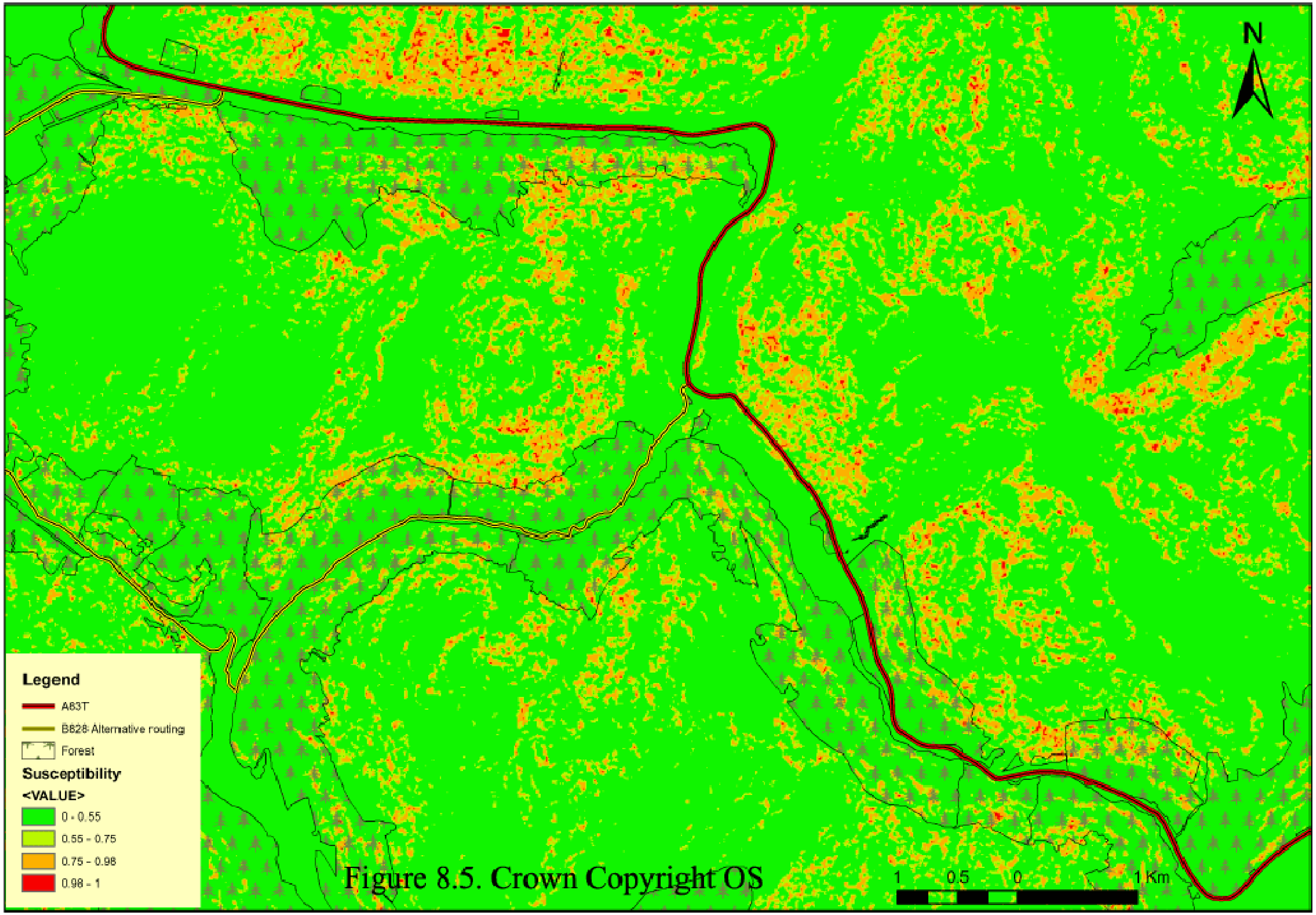


Figure 8.5. Crown Copyright OS

This method is again only possible because of the tools available in ArcMap, without which it would be impossible to accurately reclassify the geophysical parameters of an entire study area to a set of weighted values derived from a small sample of specific interest locations. The results of this analysis show a significant reduction in areas over represented as having a high probability of failure. In order to further 'focus' the output the probability layer was subjected to a 3x3 filter tool in ArcMap which removes some of the noise. Furthermore, when categorized so that only the highest probability values are represented, the output (Figure 8.5 above) may be a useful base from which to make inferences pertaining to failure susceptibility and mitigation strategies.

This ranking system was chosen over a proportional (percentage based) reclassification of the independent variable datasets. A proportional method was not as effective in reducing the over representation of high susceptibility following the application of logistic regression analysis (significant parameters were consistent with the ranked reclassification and the original data).

9 Results and discussion

The maps (figures 7.1 and 8.5) on previous pages represent probability on a scale between 0 and 1 (low to high) calculated with coefficients generated from the logistic regression model. These coefficients are based on a ‘snapshot’ of parameter data input relevant to this study area at the time of the field investigation. With respect to the parameters utilized it is prudent to reiterate the role they are considered to play in debris flow initiation. The significant parameters were identified as gradient, planar curvature and profile curvature. Collectively these three independent parameters are responsible for a key precursor to failure; stress. This data has no temporal attribute and therefore probability is a term not applicable to this output as probability implies the occurrence of an event within a given time frame. A probability scale does however represent a foundation on which to base a susceptibility classification, whereby ‘probability’ can be interpreted (without any temporal aspect) as susceptibility. Susceptibility has been classified from very low to high susceptibility and the area statistics for each method are listed in table 7 below. It is evident that the ranked reclassification method succeeded in reducing the total area delineated as having the high susceptibility classification. This is conducive to a more pertinent allocation of monitoring strategy.

Probability	Susceptibility class	Area (unaltered data)	Area (reclassified ranked data)
0-0.55	Very Low	136 Km^2	197 Km^2
0.55-0.75	Low	21 Km^2	16 Km^2
0.75-0.98	Susceptible	34 Km^2	10 Km^2
0.98-1	High Susceptible	29 Km^2	0.5 Km^2

Figure 9.0. Area statistics for susceptibility classification

9.1 Susceptibility and the original parameter data

The outcome of the initial analysis generated from unaltered independent parameter data is both reassuring and disappointing. It implies that slopes with a gradient of between 15 and 60 degrees that are subject to additional stress through excessive planar and profile curvature are most susceptible to failure (as outlined by the significance values in table 3 (step three) chapter 7). Due to the broad representation of parameter values within the unaltered data associated with failure occurrence, a larger total area is delineated as susceptible or high susceptible. Objectively whilst this is entirely valid given that this range is representative of failure, it does not emphasise that certain values may have been represented far more frequently than others. Furthermore, intermittent failures recorded on independent parameter end member values imply such values have a lesser role in initiating failure and such instances may even represent a false positive with respect to that parameter.

Fig 9.1 depicts how the results are intended for use; this map represents the same sub-section of the study area shown earlier and large continuous areas are delineated as susceptible or high susceptible (34 and 29 square kilometres respectively). This susceptibility classification is generated from unaltered parameter data and is considered overly representative of those parameter values which have had a lesser role in promoting activity. With regard to this study area, the total range of gradient values found to induce failure is extensively represented within the terrain adjacent to the A83T and therefore results in large continuous classifications of high susceptibility.

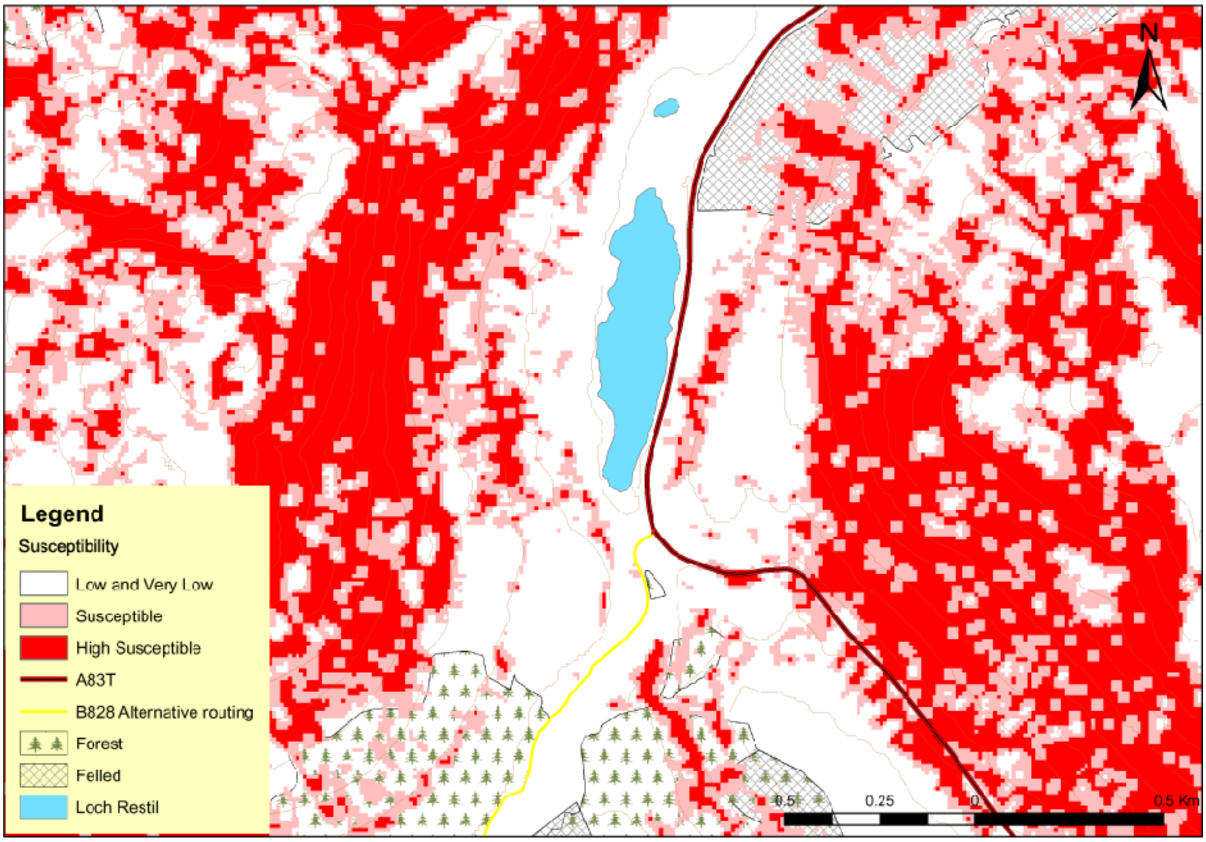


Figure 9.1. The delineation of susceptible and high susceptible areas based on unaltered parameter data.

As a result of the limited sample size and the very fact that failure occurred, a reduction of the sample size to emit these infrequent end member values is not justifiable. Unfortunately, or perhaps not surprisingly large extents of the study area are susceptible to failure based on this rationale. Likewise, those regions that represent the opposite terrain extreme (mountain plateaus, valley floors and coastal plains) are subsequently not at all susceptible to slope failure. The unaltered susceptibility classification is therefore strongly representative of 'either or' conditions, in that large portions of the study area are either susceptible or not susceptible to failure. This is in effect a true but very coarse representation of the nature of the processes in mountain environments.

There is little scope for variation in how one interprets this result, as due to the extreme end member representation of susceptibility to failure the output is of little realistic use when developing a mitigation strategy. This is partly because such large areas cannot be economically monitored and neither can it be considered realistic that such large collective areas represent such a high level of susceptibility. However, this output presents a useful conservative base. If an area is outlined as having a low or very low susceptibility based on the modelled results of unaltered parameter data, then the methodology behind the result suggests that those regions will conform to such classification. This result provides a solid representation of basic susceptibility and the output might for example be a useful base from which to undertake the most generalized monitoring efforts or to strategically place warning signs.

What the result fails to achieve is outline those areas that are most susceptible to failure. Limited resources and importance are placed on slope failure and to present a susceptibility map that states the obvious is to devalue the potential usefulness of such a system. This result is fundamentally due to the small sample size and the broad overall representation of parameter values within this sample.

9.2 Susceptibility and reclassified parameter data

In order for a susceptibility study to be of practical use, the classification must highlight those areas which are collectively most susceptible to failure, so that resources can be best distributed. The results produced from the unaltered independent parameter data arguably fail to achieve this and the large areas of high susceptibility are unfocused and of relatively little use to decision makers. However the ranked reclassification method outlined in chapter 8 has achieved a more pertinent classification of susceptibility, in that susceptibility is based on a reclassification of parameter values that emphasises those most frequently associated with failure. This method is based on the rationale that increased frequency of representation within certain value categories is likely indicative of those conditions being most inductive to failure and will therefore delineate areas most susceptible to failure. The subsequent output (Figure 9.2) represents susceptibility based on reclassified values of slope, planar curvature and profile curvature, which again were the three reclassified parameters found significant by the Logistic regression model. This method has delineated only 0.5 square kilometres as high susceptible and 10 square kilometres as susceptible.

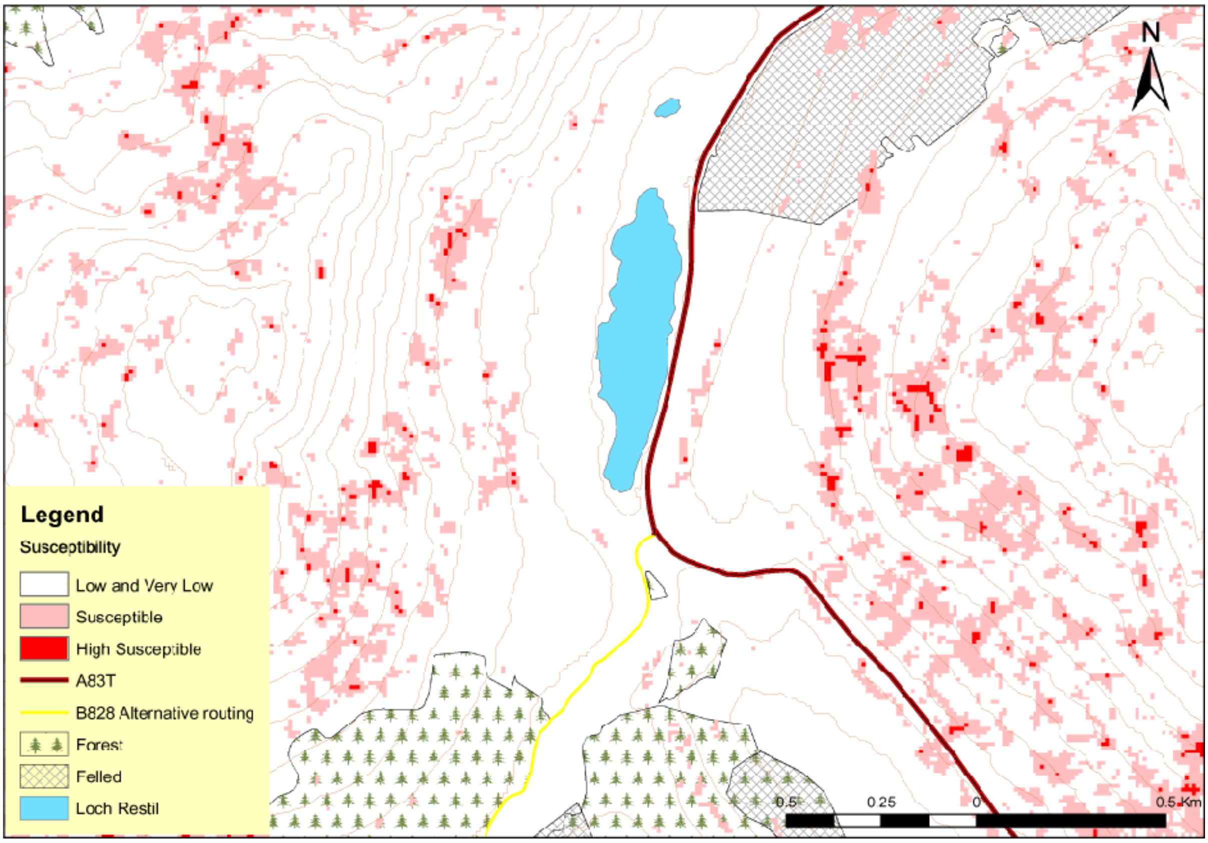


Figure 9.2. The delineation of susceptible and high susceptible areas based on reclassified parameter data.

This methodology is founded on the rule of uniformity whereby the past is the key to the future and in this case, the output is influenced by values found to be most often representative of failure and thus lacks excessive input from end member values. The three parameters on which these results are based are not only statistically significant in the model context but are arguably the three most influential stress forces to influence slope failure. They collectively facilitate increased accumulation and acceleration of runoff which promotes rapid increases in pore water pressure where the slope is already under stress. Extrinsic precipitation forcing can therefore induce slope failure. These factors taken together outline that fundamental terrain parameters play a significant role in the spatial distribution of failure susceptibility.

9.3 Susceptibility and land cover

Only parameters found to have a significant influence on the outcome of the dependent variable were incorporated into the final logistic regression model. As outlined in chapter 6 the variable land cover does not significantly affect the outcome of the dependent variable in the logistic regression model and was removed from the analysis. Therefore and based on the available data quality it is not absolutely clear to what extent land cover influences the spatial distribution of failure in this study area. Perhaps as a result of the relatively small data resolution compounded by classification uncertainty the data can not facilitate the interpretation of fine scale relationships and processes. Moreover, land cover type has many potential impacts on the susceptibility of a slope to failure and this variation can extend within a single land cover category.

However, as outlined in the literature review land cover is widely accepted as a fundamental control on susceptibility and the existing data does provide a base from which to outline generalized relationships between failure and land cover type. Such an analysis will highlight basic relationships regarding land cover type and failure that will influence mitigation planning strategy. It is therefore considered worthwhile to classify and map the effect of discrete land cover variations on slope failure. Figure 9.3 outlines the frequency of failure within land cover classes in the study area.

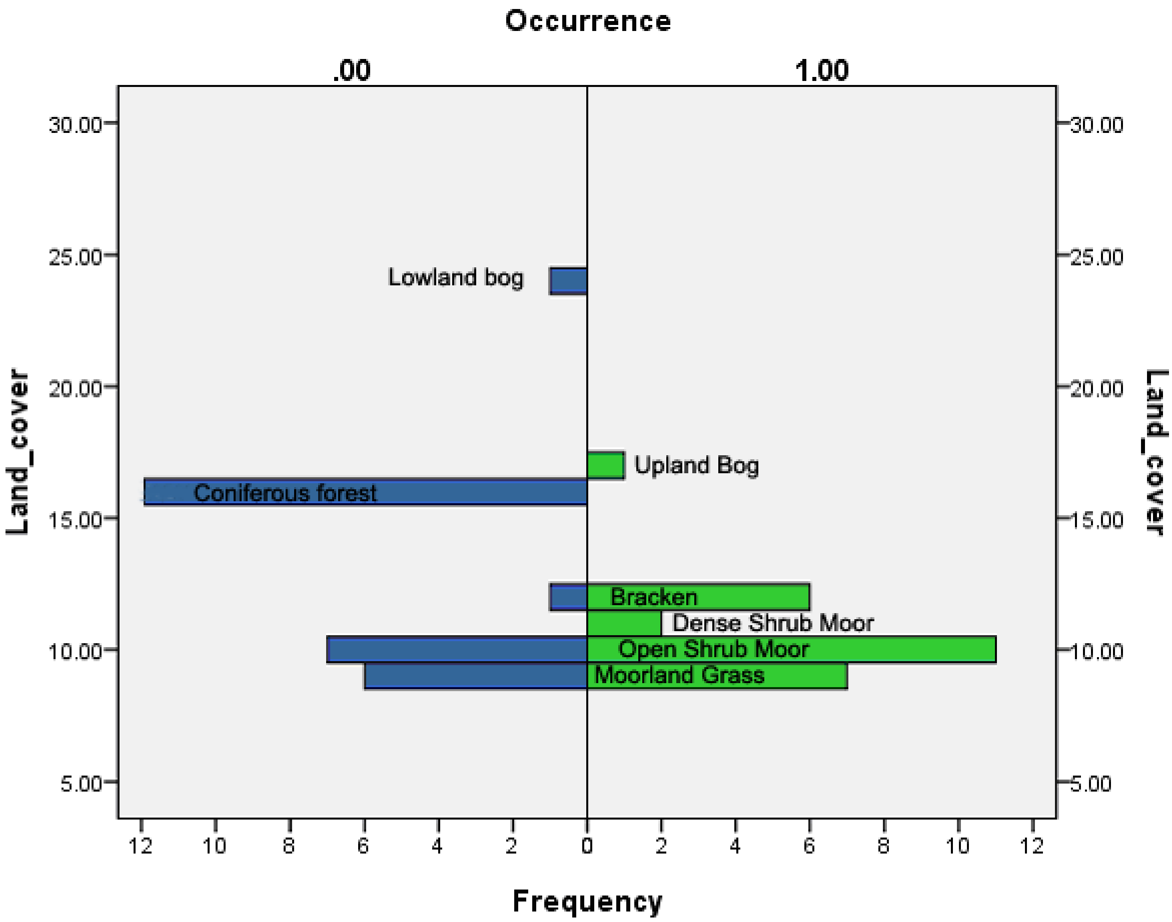


Figure 9.3. Frequency of failure per landcover class based on dependent variable location (failure to the right, non-failure to the left)

The data from Figure 9.3 can be utilized to reclassify the original land cover map so as to represent failure frequency per land cover type. To visualise where the susceptible land cover type and high intrinsic susceptibility interact to strengthen (or indeed weaken) the collective susceptibility of an area the land cover reclassification can be overlaid in the GIS with the intrinsic susceptibility classification.

Figure 9.3.1 contains area calculations of intrinsic susceptibility and intrinsic high susceptibility relative to land cover classes on which they exist, Land cover classes are listed from low to high susceptibility, with coniferous forest having no instances of failure to Open shrub moor which has the highest density of failure. The figures show that small proportions of high susceptibility located within land cover classes such as coniferous forest may in reality be less susceptible because of the land cover type. The scenario is repeated for areas of intrinsic susceptibility. Areas of low and very low intrinsic susceptibility were not assessed.

Land Cover	Area intrinsic high susceptibility	Area intrinsic susceptibility
Coniferous forest	0.07 km^2	1.6 km^2
Upland Bog	0.02 km^2	0.3 km^2
Dense shrub Moor	0.01 km^2	0.5 km^2
Bracken	0.04 km^2	0.3 km^2
Moorland Grass	0.05 km^2	1.4 km^2
Open Shrub Moor	0.31 km^2	5.5 km^2

Figure 9.3.1. Intrinsic susceptible and high susceptible distribution within land cover type.

These findings imply that areas delineated as susceptible and high susceptible based on results from the logistic regression model compounded by a high failure density land cover classification may be considered priority for further monitoring and investigation. Whereas for example forested areas delineated by the model as susceptible or high susceptible but have not been subject to slope failure imply that forest has a stabilizing effect on terrain. Therefore attention may shift from forested areas. As outlined earlier the density of failure occurrence within each land cover type is perhaps the best and most objective form of analysis possible with available data. This method succeeds providing a basic impression of land cover type/failure relationship. In this study area highest failure frequency is in areas classified as ‘Open shrub moor’ and second to this was ‘Moorland grass’, this is mirrored in the distribution of modelled susceptibility and high susceptibility per land cover type.

On the ground, while the land cover nomenclature quantifies the land cover type it does not provide information at the species level or indeed concerning the condition of the vegetation. It is at this level that small variations in land cover conditions can act to destabilize slope and unfortunately, this is perhaps one of the most difficult independent parameters to classify and model and to do so has certainly been beyond the scope of this study. It is perhaps likely that in order to generate a better understanding of land cover failure relationships in this area a more subjective assessment ought to be made prior to the implementation of a slope monitoring strategy. So that whilst broader areas of susceptibility have been delineated by the methods utilized thus far, it is considered that strategists be left to implement their own knowledge when assessing the susceptibility of land cover on site in the field. These ‘micro scale’ variations were evident during field work in that certain areas appeared to have a highly established vegetation/soil /drainage structure whereby the land was able to cope with extreme precipitation and run off. As a result of the nature of the land cover data there is nothing to differentiate between these areas of established vegetation (within same land cover category) and areas that are not so stable (perhaps as a result of over grazing, soil variations and exposure).

Land cover can therefore be considered an important variable which requires further investigation and analysis pertinent specifically to regions delineated by the model as susceptible or high susceptible. From the results of this study it is recommended that all such areas be investigated, regardless of land cover in order to facilitate a better understanding of land cover failure relationships and to prevent a repeat of catastrophic failure in 2004 which occurred even within forested areas. A key outcome of these results is that land cover can be attributed to failure susceptibility on a large scale however it will require further investigation and implementation of site specific investigation and monitoring in order to understand the effect that subtle variations in vegetation conditions can have on slope failure.

10 Implications of the model output

With respect to the modelled results and subsequent susceptibility maps it is important to reiterate that the intrinsic parameter data layers utilized in the classification were derived from one data set. The Ordnance Survey 10 metre DTM elevation raster is among the best available and as outlined in the methodology every step was taken to ensure that the data was prepared to the best standards possible. Every effort was made to source the most highly regarded and effective algorithms for slope, flow accumulation and curvature calculations. However, the output remains a model, which is subject to data inaccuracies and generalizations within the parameter data. The analysis and output are uniform, which will allow for action if discrepancies or inaccuracies are found during subsequent field investigations and /or the implementation of model testing.

Results generated from both unaltered and reclassified ranked data are outlined and presented in this paper. The result of the latter is indicative of 'optimum' geophysical conditions which have previously facilitated failure in this study area and is considered a practical delineation of susceptibility from which to further monitor and investigate the failure process in this area. The methodology utilized is made possible by the data interpretation and manipulation capabilities of the GIS environment. Without the GIS technology which lends itself so well to this type of raster data manipulation and analysis it would not be possible to reclassify data and undertake this type of analysis so as to generate such a comprehensive susceptibility classification. Whilst the model generates an objective output the GIS enables the output to be tuned so as to delineate only the most susceptible areas. For example it is possible to be quite selective and consider only those cells with the highest susceptibility rating for subsequent monitoring strategies, although how one may choose to categorize susceptibility is ambiguous and unfortunately there may be a fine line between spreading resources and wasting them. The aim of generating this model was to reduce the uncertainty that may act to hinder a slope monitoring project however such uncertainty will remain if the model fails to delineate areas of high susceptibility, is too liberal when determining which areas constitute high susceptibility or fails entirely.

It is therefore that models require development and testing so as to determine which methods are most effective and could therefore be applied over a broader area. An advantage of this modelling method is that it is highly adaptable to both available data and end user requirements, so that alternative methods and strategies can be developed and tested in an effort to obtain the optimum balance pertaining to the specific instability processes and characteristics of certain geophysical environments (problem areas). Evidently a key aspect lacking from this study is a method of testing the model which is fundamentally due to temporal constraints in that to test the output, time and activity are required. Ideally, for example in this study area, the model output can be utilized to locate areas considered most susceptible to failure so as to determine optimum monitoring sites and actually determine how susceptibility is manifested over time and in reality. Many studies 'save' a proportion of known failure (dependent variable) locations from analysis so as to test the output (Chung & Fabbri, 2003) and while this would have been the optimum method by which to test the model, the study area is rather small and the sample of dependent occurrences was not sufficient to warrant the exclusion of a test sample. Presently then, and until further failure events there is no way to assess the accuracy of this model and subsequent outputs.

There are however promising examples that ‘confirm’ the ability of the model to delineate areas of high intrinsic susceptibility. As outlined previously in this paper the Scottish roads network was affected by multiple cases of slope failure following extreme rainfall in August 2004. In 2006 a paper (Winter *et al*., 2006) pertaining specifically to this activity was published in the *Quarterly Journal of Engineering Geology and Hydrogeology* which included a photographic feature. These photographs featured a failure that occurred on the northern boundary of the study area, on a slope not included in this study despite lying within the data coverage. It depicts an area modelled by this study as exhibiting zones of high susceptibility during a period of high risk and clearly captures the zone of failure initiation and therefore offers an opportunity to ‘test’ the model output in a geophysical setting equivalent to that utilized during model development. The images confirm that the model has identified with apparent accuracy the area in which failure initiated without over representing the aerial extent of high susceptibility. This type of flow would be classified generally as a debris flow but more specifically as hillslope flow and it is apparent that flow has been dictated latterly by the path of a small stream gully. Flow had extended out with this gully cutting new channels and depositing material over quite a large run out lobe which completely engulfed the road below (A83T) and endangered residential property. This type of event highlights the risk to the road network when transecting such terrain and specifically during extreme precipitation events, in that whilst the zone of initiation lies at around 350m, activity has severely affected the road 325m below.

In October 2007 heavy precipitation resulted in a significant translational slide within the actual study area. This presented a hazard to the road which was closed for weeks as a result of the risk presented by the activity. The model correctly predicted the location of this event and provides further justification for the development of this technique within this sector.

These examples outline the complications in monitoring slopes for failure susceptibility within this type of varied geophysical setting and why a model would likely reduce the workload involved. It is evident that there is a correspondence between the model output and reality during the aforementioned periods of activity. This implies that failure zones and even small scale translational slides and flows may develop under certain geophysical conditions which can be delineated by this model. However, the model implies a broader extent of flow activity than that which is evident in the field which raises interesting questions of the geophysical and geoecological conditions required to promote a failure zone or potential failure zone to an actual failure event. The proximity of existing drainage channels and vegetation variations may have a significant role in controlling the progression from potential failure zone to actual failure and subsequently the magnitude and extent of failure. This is complex as a the proximity of drainage channels can act to both mitigate failure by ensuring effective drainage yet a channel can also exert a destabilizing effect and provide a route of least resistance for debris flow. The implication is that whether or not stress zones develop into failure events and the extent of flow likely depends on the availability of some form of channel such as a stream or debris flow and the level of stability provided by vegetation and geophysical conditions. This reiterates the need for further investigation into these issues.

11 Recommendations

The outcome of susceptibility modelling outlined in chapter 8 implies that slope failure is a potential hazard within this region. The susceptibility analysis therefore provides a base from which decisions can be made concerning what action (if any) is necessary to assess and/or mitigate the effect these sites may have on the road network. The results of the model were classified into four categories: very low susceptible, low susceptible, susceptible and high susceptible. As outlined previously areas delineated as susceptible and high susceptible account for 10 and 0.5 square kilometres respectively in an area of 230 square kilometres.

Areas of high susceptibility can be considered as 'most likely' to promote failure in the event of extrinsic forcing from excessive precipitation and which therefore warrant monitoring for future risk given variations in precipitation conditions. It is widely accepted that the primary cause of failure in this region is excessive precipitation therefore the next logical step in this assessment is to initiate a programme of slope monitoring and indeed precipitation monitoring so as to generate an understanding of the response generated in these susceptible areas to excessive precipitation. The excessive cost of action may not be considered worthwhile or indeed may exceed the cost of removing debris and seasonal repairs. Furthermore susceptibility and risk do not individually amount to an actual hazard unless there it is possible the activity or the effect of activity could intersect the road. This investigation does not assess the likelihood of susceptible areas affecting the road and it is considered that further investigation be orientated towards assessing potential risk. Social responsibility would imply that given the identification of risk to infrastructure, property, services and persons in this study area, remedial measures may be necessary (Popescu, 2000).

On these grounds it is recommended that a monitoring programme be initiated whereby field investigation focuses on areas delineated as high susceptible and susceptible. Despite the apparently small cumulative area classified as such, the locations are distributed throughout the whole study area and are challenging to reach. However the accurate location of these sites can be facilitated by GPS navigation and all terrain vehicles can provide access to the sites. Furthermore a significant proportion of the sites do not require further assessment for the purpose of actual hazard analysis as they cannot physically affect the road. Monitoring of sites deemed to warrant further assessment can be carried out by the distribution of the following tools:

1. Piezometers for the continual monitoring of pore water pressures in areas of high susceptibility

2. Motion sensors so that any movement in the soil can be identified and assessed.

3. Precipitation gauges

It is considered that the above equipment correctly distributed will facilitate an improved understanding of rainfall/pore water pressure/failure relationships that appear to control the temporal distribution of activity in this region. Such a study would be an interesting addition to this investigation and eventually it is hoped that extrinsic precipitation forcing can be incorporated into this type of model so as to quantify hazard. The GIS utilized here in the delineation of susceptible areas can be modified for use on a daily basis with respect to the regular monitoring of slope stability conditions. Piezometer and precipitation data can be monitored real time on a site by site basis by regulated transmission of data so that variations can be monitored specific to their location. GPS sensors equipped with an altimeter can transmit data so that inferences be made on slope movement. This data can be utilized in site specific investigations so as to better understand slope instability and given time, hazard periods will be predictable which could allow roads to be closed.

Remedial measures

This study is a susceptibility analysis, remedial measures are dependent on many external factors that have not been dealt with in this study. However, following a monitoring strategy and if deemed necessary remedial measures ought to focus on the primary cause of the activity. In this case it may be that excess precipitation and stress are inducing failure, therefore remedial measured would focus around improving drainage and stability. It is likely that the cost of such action in an area such as this would be highly prohibitive and that it may likely be considered more effective to simply close the road during periods of perceived hazard. However, remedial efforts may be necessary if failure frequency increases spatially and or temporally. If so the most effective form of remedial measure in this type of terrain would likely be those that increase the efficiency of drainage so that pore water pressures are no allowed to rise to a level whereby they act to transform susceptibility to risk.

Disclaimer

This study was intended as a test case to determine if methods previously applied in other countries to identify the susceptibility of slope to failure are applicable within Scotland. Whilst it does not propose to delineate hazard or risk it is evident that as a result of the route taken by the A83T there are certain areas within which failure could potentially result in damage and/or disruption. The model and results developed in this study amount only to a susceptibility assessment, they do not claim to be an accurate representation and absolutely do not delineate risk or hazard. There are many potential errors in data and reasons why this interpretation could include false positive and false negative results which is why further field investigations and monitoring of susceptible areas are advised. This subject and particularly the multivariate statistical analysis of independent parameters will benefit from increased availability of existing parameter data and indeed the development of data pertinent to parameters not yet included so as to facilitate both a broader and more accurate criteria on which to model susceptibility. This study area is representative of only a proportion of Scottish terrain, the findings from this study apply to this area only and it is therefore an interesting prospect to undertake similar assessments in regions of differing geophysical properties so as to assess the applicability of methods in different geophysical environments.

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