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SUMMARY

1 Soil erosion is both a natural and man-induced phenomenon with wide-ranging implications for the natural heritage and for sustainable soil management. While localised soil loss and erosional features may have limited impacts, there are a number of off-site effects which may have more severe consequences. To date, there has been no published systematic national evaluation of the soil erosion risk in Scotland.

2 This project set out to develop a transparent, rule-based model for assessing the inherent risk of Scottish soils to erosion by overland flow. This assessment was made on the basis that the soils were free of vegetation, thus giving a baseline estimate of the sensitivity to erosion.

3 The model was then applied to existing soils and topographic datasets to produce a spatial estimate of the inherent erosion risk throughout Scotland. The maps and model will allow the development of management and awareness programmes to help minimise the instances of erosion in sensitive areas.

4 Recent literature was reviewed to establish the suitability of existing models, for example, the Universal Soil Loss Equation. However, no model was found that was applicable to the edaphic and climatic conditions found in Scotland and so a new rule-based model was developed which took cognisance of existing process-based models.

5 The derived rules were based on three variables: slope, runoff and soil texture. Firstly, the slope and runoff were combined to estimate the erosive power of overland flow. This was then combined with the erodibility of the topsoils to give an overall estimate of the erosion risk. The classification treats soil erosion as a static land quality.

6 These rules were then applied using two spatial datasets: the 1: 50 000 scale Ordnance Survey digital elevation model and the digital coverages of soil texture and HOST runoff classes derived from the 1: 250 000 scale national soil map of Scotland. This produced a set of five 1: 250 000 scale maps showing the soil erosion classes throughout Scotland.

7 From an estimated total land area of 7.7 million hectares, over 4 million hectares of Scotland was classified as having a moderate risk of erosion by overland flow, and a further 2.5 million hectares have a high risk. Summary statistics are presented for each area in SNH's framework for Natural Heritage Futures..

8 This project has established the inherent geomorphological risk of soil erosion by overland flow. Future work should aim to incorporate land cover data into the rule-base to allow an assessment of the actual erosion risk.

9 The project revealed that there is a significant lack of objective data on the erodibility of Scottish soils (both organic and mineral). Experimental procedures should be put in place in order to provide estimates of erodibility for Scottish soils to improve the decision rules.

10 There should be a move towards the use of more process-based models to determine the soil erosion risk for detailed or site specific investigations. This would also allow an appraisal of the effect of rainfall variability, land use and land management on the risk of soil erosion.

KEYWORDS: soil erosion, overland flow, geomorphology, decision rules, rule-base.

1 INTRODUCTION

Soil erosion is a natural phenomenon but its rate and intensity can be increased by human activities. Soil erosion has wide-ranging implications for the natural heritage and for sustainable soil management. While localised soil loss and erosional features such as rills and gullies may have a limited impact both spatially and in severity, there are a number of off-site effects which may have more severe consequences: for example, streambed aggradation, increased turbidity, increased flood risk and eutrophication of rivers and lochs. There have been a number of documented instances of extensive amounts of erosion to Scottish soils but in localised geographical areas (Hulme and Blyth, 1985; Spiers and Frost, 1985; Watson and Evans, 1991; Birnie, 1993; Kirkbride and Reeves, 1993; Grieve et al., 1994; Davidson and Harrison,1995; Wade and Kirkbride, 1998). Although both Frost (1993) and Wade (1998) assessed the erosion potential in Fife, to date there has been no published systematic national evaluation of the soil erosion risk for Scotland.

This project, funded by both SNH and SOAEFD, set out to develop a rule-based model for assessing the inherent erosion risk of Scottish soils and then to apply this model to existing soils and topographic datasets only, to produce a spatial estimate of the inherent erosion risk throughout Scotland. The soils were assessed on the basis that they were free of vegetation. The work will allow the development of management and awareness programmes designed to help minimise the instances of erosion in sensitive areas.

2 OBJECTIVES

The risk of a soil to erosion derives from its inherent mechanical stability and the occurrence of triggering events such as rainfall or snowmelt. Management factors, such as the type and extent of vegetation cover, will also influence the actual erosion risk. The inherent mechanical or geomorphological stability derives from the combined effect of topographic context (slope angle and slope position) and from soil properties such as topsoil texture.

Ideally, soil erosion risk should be expressed in terms of a probability estimate and any model derived to predict this risk should be sufficiently flexible to be used as a tool to investigate the soil's response to changes in land management or climatic conditions. These objectives would be best achieved through the use of process-based erosion simulation models. However, these types of models require large amounts of data in order both to run and be calibrated and, therefore, could not be used at a national scale. An alternative approach is to develop a rule-based model which could be implemented within a GIS to produce a spatial estimate of the inherent potential for soil erosion at a reconnaissance scale. Areas predicted as having a high risk could then be targeted for more detailed process-based studies. Specifically, the required outputs of the project were:

1. to establish what variables are important in determining the inherent geomorphological risk of soil erosion by overland flow and to derive a rule-based model to predict this risk;

2. to utilise the spatial datasets held by MLURI and the derived rule-based model to produce a national 1:250 000 scale map of this inherent risk.

In deriving a rule-based model and implementing it at a national scale, certain assumptions had to be made:

1. all soils were assessed on the basis that they were free of vegetation;
2. only erosion related to surface runoff or overland flow was considered (thus, wind erosion or other forms of mass movement were excluded);
3. no consideration was made of the dynamic factors which affect erosion (for example, land management practices or occurrence of triggering events like rainfall or rapid snowmelt).

These assumptions recognise the fact that soil erosion risk is a dynamic feature of the landscape and that the risk changes according to a number of factors such as the antecedent moisture contents of the soil, its infiltration rate and storage capacity, as well as amount and intensity of rainfall or rapidity of snowmelt. However, it was not possible within the scope of this study to model the effects of single rainfall events or the effects of different vegetation types. Thus the model only considers the geomorphic risk of soil erosion by overland flow which is essentially a static land quality. Also, by assessing the erosion risk on the basis that the soils were free of vegetation, the binding action of the roots (which will vary with the type of vegetation) can be ignored. As the classification presents the worst case, the soils in all risk categories will have the potential to erode.

3 REVIEW OF EXISTING MODELS

As there was no current nationally applicable rule-based soil erosion assessment model available for Scotland, the first task was to review recent literature to establish the existence of any suitable model from other geographic areas. However, since such empirical models are generally only locally applicable, cognisance was also taken of the existing process-based models.

Perhaps the most widely known soil erosion model is that developed by Wischmeier and Smith (1978), called the Universal Soil Loss Equation (USLE). In this model a number of independent factors are multiplied together to give an overall rate of soil loss. Although this model was applied by Frost (1993) in the Loch Leven catchment, there are a number of reasons why it was not used in this study. Being largely empirical, it may not be applicable to Scottish conditions; it fails to deal with soils where organic matter contents are greater than 4%, and it requires detailed knowledge of the intensity of rainfall events. Most Scottish soils will have organic matter contents in excess of the 4% threshold. Rossiter (1990) developed a model to predict the erosion risk of US soils, which utilised some of the data used to characterise soil map units, such as slope categories and permeability. However, the erodibility index used in his model was also derived from the USLE.

The EU funded CORINE project (Briggs and Giordano,1992) developed a soil erosion risk assessment model applicable to Europe which used the USLE as a conceptual basis. The datasets used to derive the assessment were those available at a European scale. For example, most of the soil data were derived from the 1:1 000 000 Soil Geographical Database of Europe which has few variables in common with the USLE soil erodibility index. One of the main problems with this classification is that there is no means of classifying soils with organic surface layers. However, there were certain features of the classification that could be used in this study; for example, the principles of scientific rigour in methodology, the need for transparency in the rule-base and the need to base the classification on existing data. The model of Briggs and Giordano (1992) predicts only the potential erosion risk and offers no prediction of the amount of soil loss.

Perhaps the most important reason why the USLE (and its derivatives) is not applicable to Scotland is that the soil erodibility index is based on empirical results from experimental plots in the USA where the influences of the climate and vegetation, in particular, would result in a different set of soil conditions to those found in Scotland. Thus it is unlikely that these empirical results would be applicable to Scottish soils.

More recently, a number of process-based soil erosion models have been developed. These models set out to represent the processes involved in soil erosion and as such should be applicable in any environment. However, they require a great deal of detailed information both to calibrate and run and, therefore, were not suitable for use in this project. Nevertheless, these types of models can be useful in the selection of parameters for the rule-based model.

One of the most relevant of these process-based models is EUROSEM (Morgan et al., 1998) which was developed by a number of European researchers. As it is event based, this model estimates the hydrological response and sediment transport within any given rainfall episode. As the model requires a large number of parameters to be determined, the authors have given lists of average values for many of them. Amongst the most important are those for particle detachability by both raindrop impact and by water flow. These values are given for a range of soil texture classes. These values were determined from replicated field measurements on European soils. A key observation is that the rank order of these indices of 'erodibility' do not agree with that of the USLE.

The National Soil Erosion Research Laboratory (NSERL) in the USA has also developed a process-based soil erosion model called WEPP (Water Erosion Prediction Project). This model uses values for erodibility in a similar fashion to EUROSEM and has been published by Flanagan and Nearing (1995). The rank order is similar to that given for the EUROSEM model. Crucially, WEPP was designed as a replacement for the USLE and this change in the perception of a rank order of erodibility (also listed by texture class) adds further weight to the argument for not using the USLE in Scotland.

The overall conclusion was that there was no existing rule-based model suitable for use under Scottish conditions. However, the principles and data given in published

process-based soil erosion models allow the construction of a new rule-based model in such a way as to ensure that any future potential use of these more detailed, process-based models (for example, in detailed, site specific investigations) will be an evolutionary process and unlikely to change significantly the initial risk assessment.

4 PROCESSES AFFECTING SOIL EROSION

Erosion of mineral soils by overland flow involves the detachment of soil particles and their subsequent transport. Hence, the factors which influence the erosion risk are soil particle detachability or the mechanical strength of the soil aggregates, the occurrence of triggering events such as rainfall or snowmelt which initiate surface flow and management factors such as land use and vegetation cover. The inherent geomorphological stability is determined by slope angle, slope length and position, as well as the intrinsic soil properties.

Soil particle detachability describes the process by which soil aggregates disintegrate into their constituent parts which can then be transported. This depends on the mechanical strength of the soil which in turn varies with moisture content. In many models, soil texture is seen as a surrogate for soil strength or as a carrier of this information (a type of class pedotransfer function). Soil strength is a complex attribute influenced by the amount and type of clay and by the amount of organic matter. Soils with <3.5% organic matter are considered to have inherently unstable aggregates (Greenland et al.,1975). As roots can have a binding action on the soil, soil detachability is generally determined on bare soil surfaces.

Overland flow is initiated when either the rainfall intensity is greater than the infiltration rate of the soil or when rainfall exceeds the storage capacity of the soil. The latter condition is thought to be much more prevalent in Scotland. It is overland flow which causes rill and gully development and is responsible for the rapid transport of sediment. Subsurface flow is also a contributory factor but is less evident. Once initiated, the erosive power of this overland flow is enhanced by both slope angle and slope length: the steeper and longer the slope, the more likelihood there is of erosion. Slope form, for example, convexity or concavity, may also affect the erosive power of the overland flow.

Early work on evaluating soil erosion by overland flow placed a great deal of emphasis on the rainfall intensity necessary to break down soil aggregates. However, recent work in Scotland (Kirkbride and Reeves, 1993) indicated that soils can erode under conditions of low intensity, but prolonged, rainfall or under conditions of rapidly melting snow (Wade, 1998). This implies that the inter-relationship between the degree of saturation and soil strength may be of more importance than rainfall intensity in Scotland. Also, as rainfall is a highly dynamic property with a high degree of temporal variability, it was difficult to incorporate such a property into a rule-based model which has no element of probability. Therefore, rainfall was not included in the rule-base.

5 DEVELOPMENT OF THE RULE- BASE

5.1 Introduction

The development of the rule-base to assess the potential for soil erosion by overland flow in Scotland took place using a knowledge of soil erosion processes but against a background of limited data availability. Thus while estimates of soil permeability and storage capacity were desirable, the only nationally available data on the physical condition of the soil was the Hydrology of Soil Types classification (Boorman et al., 1995). Similarly, there were no data available on the mechanical strength of soil aggregates. Therefore, soil texture was used as a surrogate for this parameter. Inevitably this led to a degree of compromise, but the rules were constructed in such a way as to allow implementation at a more detailed resolution.

The specified output of 1: 250 000 scale maps dictated the spatial datasets which were available for use. However, the rules will be applicable at a more detailed level with minor enhancements. Initially a decision tree approach was envisaged, but this proved to be impractical due the number of classes and datasets which were to be combined. This rendered the approach cumbersome and repetitive. Instead, a series of tables was developed which maintained the desire for transparency in the rules as well as more effectively showing the relationship between the parameters being combined. It was also easier to see the effects of mis-classifying data from the tables. The sequence in which the decision rules were applied (slope, runoff, soils) was also important. This reflects the overriding influence of slope on the energy available for the transportation of soil particles.

5.2 Slope

As the slope increases, the amount of energy available to any overland flow also increases. There are a number of potential slope classifications that could be used, for example, the CORINE project classes (Briggs and Giordano,1992) or the USDA classes used by Rossiter (1990). However, the former lack detail, while the latter have overlapping classes. Other international slope classifications, such as that used by the FAO (FAO, 1990) as part of their soil description procedure, had too many classes; for example, the FAO system had 10 classes, five of which were less than 3 degrees. As the erosion risk potential being identified was the inherent geomorphological risk, it was felt that the slope classes should have some significance in geomorphological terms. The classification selected is that published in Young (1972) which is based on characteristic and limiting angles found within erosional environments (Appendix 1). Six classes have been identified (Table 1). The first, $< 2^{\circ}$, describes the slopes where soil erosion is the least likely to occur, while the last, $>30^{\circ}$, delineates those slopes which are approaching the limiting angle for unconsolidated material with pore water pressure (Young, 1972) and are likely to be inherently unstable under all conditions. The remaining four classes (Table 1) represent increasing energy availability as the slope steepens. The unequal increments in slope classes give the classification greater refinement on less steeply sloping land. As the slope increases, there was a corresponding increase in erosivity of the overland flow, however, the amount of overland flow was also important.

Table 1. Slope versus runoff to derive erosive power of overland flow

Percentage runoff	Slope categories (degrees)					
	<2	2-4.9	5-9.9	10-17.9	18-30	>30
<20	a	b	c	d	e	Slopes unstable
20-40	b	c	d	e	f	
>40	c	d	e	f	g	

5.3 Runoff

The amount of runoff generated during a rainfall event depends largely on the nature and properties of the soil, in particular its permeability and storage capacity. As these are complex soil properties with a high degree of spatial variability, there were few real measurements available. The recently developed Hydrology of Soil Types classification (HOST) which describes the hydrological response of UK soils (Boorman et al., 1995) has been calibrated against the hydrological index of Standard Percentage Runoff (SPR). The HOST classification itself was developed from a consideration of how the physical condition of the soil affected the flow regime and can be used as a surrogate for measured soil hydrological properties.

The HOST classification is based on 11 conceptual models of the dominant pathways of water movement through the soil and substrate. These models were modified according to the rate of flow through the soil and substrate to give a 29 class system. Although the SPR index was primarily derived to predict the fast response of rivers and does not strictly represent overland flow, it does allow the ranking of soils according to the proportion of rainfall likely to run off and it is the only nationally available dataset capable of predicting runoff. The SPR varies from 2 to 60%.

Three categories of runoff were identified which reflect the flow characteristics of the soil (Table 1). The first (<20%) represents soils with a relatively high infiltration rate, for example, soil derived from fluvioglacial sands and gravels. The second group (SPR between 20% and 40%) all have a mineral topsoil which allows some infiltration while the third group (SPR>40%) have primarily (but not exclusively) organic topsoils which tend to inhibit infiltration and are slowly permeable. This, in part, accounts for the occurrence of soils with 40% runoff on less than 2° slopes. It must be remembered that a proportion of this 'runoff' is in fact rapid flow through the soil and substrate to rivers and streams. This is particularly true for the alluvial soils where rainfall has only a short distance to travel to the river and therefore have a high SPR value. In strict terms, hydrologists would describe SPR as the rapid response component of stream flow.

The erosive power of the overland flow is a function of the amount of water and the energy derived from gravity estimated from the steepness of the slope (Table 1). There was clearly an element of uncertainty associated with this determination, for example, the SPR values can vary by up to 15% in a class and SPR itself is not strictly overland flow. The non-linear increase of erosive power (calculated by multiplying the slope angle with the SPR) necessitated a slight adjustment to the

categories where slopes are steep (18-30°) but the predicted runoff is less than 20%. In this case, the erosive power was thought to be more closely related to the preceding slope category and those where the slopes were less than 10° but runoff was greater. Had the slope classes extended beyond 30° in the classification, this problem would be exacerbated.

5.4 Soil susceptibility - mineral soils

The susceptibility of mineral soils to erosion depends largely on the ability of the topsoil aggregates to resist breakdown and hence transportation. This aggregate strength is not a static property; rather, it varies throughout the year in response to moisture content, and through space in response to the clay and organic matter content. Once the aggregates have disintegrated, then the smaller particles will be more easily transported than the larger ones. In the absence of aggregate strength measurements, it is normal to relate the erodibility of the soil to its texture, which also indicates the proportion of fine particles that would be available for transport. Due to the protective action of vegetation, the soil erodibility was assessed under conditions of bare soil.

Each soil erosion model defines the relationship between topsoil erodibility and texture in a slightly different way. This made it difficult to select an appropriate ranking for Scottish mineral soils. It was decided to dismiss those which had their basis in the USLE due to the requirement of that classification that organic matter content should be < 4%. The values listed for the EUROSEM process-based model seemed to reflect best the documented evidence of soil erosion in Scotland (Spiers and Frost, 1987; Kirkbride and Reeves, 1993; Davidson and Harrison, 1995; Wade and Kirkbride, 1998). However, these values were rather complex and referred to measured values for both detachability by raindrop impact (in grams per unit of rainfall energy) and by overland flow (soil strength) and for soils at different moisture contents. In order to try and obtain a consensus, the various elements of this model and of the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) were reviewed to establish a ranking of erodibility in broad texture classes. Although a replacement for the USLE, the soil data used in the WEPP model has a wider range of organic matter contents than its predecessor and is based on measured values of soil strength and sediment yield.

A three class system for mineral soils was devised from the ranked texture classes, with fine textured topsoils being the least erodible and coarse textured mineral topsoils the most erodible. Table 2 shows the British Soil Texture Classification (BSTC) texture classes which occur in these three groups. There is considerable uncertainty in the rules for allocating erodibility classes to the soil texture groups, partly due to the need to draw a consensus from the disparate information available, and partly due to the lack of corroborative evidence. Although it is known that the more coarse textured soils of eastern Scotland are prone to erosion, these are also the areas with the greatest proportion of arable land and hence where there is likely to be bare soil at some time in the year. Further uncertainty arises as the texture classes encompass a wide range of clay contents. It is the clay (along with organic matter) that binds the soil particles together and affects aggregate stability.

Table 2. British Standard Texture Classification classes grouped by Soil Erodibility class

	Soil erodibility texture class		
	Fine	Medium	Coarse
BSTC texture class	Clay Sandy clay Silty clay Silty clay loam	Sandy clay loam Clay loam Silt loam Sandy silt loam	Sand Loamy sand Sandy loam

Although soil texture is taken as the discriminating attribute, the literature also points to soils with low levels of organic matter being more erodible (Greenland et al., 1975) and a case could be made for modifying the above table to include soils with lower organic matter contents. In general, soils with less than 3.5% organic matter would be more erodible, while those with more than 10% organic matter would be less erodible (that is, those described as humose).

5.4.1 Decision rules for the determination of the potential erodibility of mineral soils

By combining the slope/runoff classification and the Soil Erodibility texture classes (Fine, Medium and Coarse), a ranking of the overall potential erodibility for mineral topsoils in Scotland can be devised (Table 3). This table ranks the mineral soils according to the likelihood that they will be eroded by water when the soil surface is bare from least likelihood (category 1) to the greatest (category 9).

Table 3. Rank order of erodibility of mineral soils

Soil Erodibility texture class	Erosive power						
	a	b	c	d	e	f	g
Fine	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Medium	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Coarse	*3*	*4*	*5*	*6*	*7*	*8*	*9*

5.5 Soil susceptibility - soils with organic surface layers

None of the reviewed models dealt effectively with soils with highly organic surface layers, such as peats, peaty gleys, peaty podzols and humus-iron podzols. Grieve et al. (1994) conducted an extensive literature review of soil erosion in the uplands of Scotland and concluded that most studies were too site specific to enable the development of a national assessment. Unfortunately, most of these organic and organo-mineral soils are to be found in the uplands. From the literature (for example, Philips et al., 1981; Birnie and Hulme, 1990; Birnie, 1993; Grieve et al. 1995; Carling et al., 1997), the causes of erosion on organic soils are complex and may rely on such factors as land management and land use or climate change, which makes the derivation of an inherent risk difficult.

The mechanisms of erosion of organic soils may not be the same as those for mineral soils; for example, many organic soils are eroded when a surface crust dries

and detaches (Hulme and Blyth, 1985), whereas the aggregate strength of many mineral soils increases as they dry. While there are data on the mechanical strength of mineral soils (for example, values given for use with the WEPP and EROSEM models), there are no comparable values for organic soil horizons. Carling et al. (1997) also found difficulty in obtaining directly comparable measurements of soil penetration resistance for mineral and organic soils. They did report, however, that penetration resistance decreased as the degree of humification increased. Since the processes of erosion appear to be different in organic soils than in mineral soils, a common set of rules would not be appropriate. Therefore, it was decided to devise sets of rules specific to mineral soils and to organic soils.

5.5.1 Decision rules for the determination of the potential erodibility of organic surface layers

In the assessment of potential erodibility of mineral soils, it was assumed that the soil surface was bare of vegetation. This assumption should also be made for the assessment of both the organic soils (peats) and those with organic surface layers (those described as 'peaty' or 'humus') although it is recognised that these organic layers could not have developed without a vegetation cover. Although essentially stable when vegetated (Carling et al., 1997), organic soils and organic surface layers have been shown to be inherently highly erodible when bare (Hulme and Blyth, 1985). These latter authors witnessed a dramatic erosion event in the relatively gently sloping peatlands of Shetland where large quantities of dried peat were removed from gullies. However, Carling et al. (1997) suggested that a bare peat surface was not erodible even by fast flowing water. Both of these observations, however, were made on different peat surfaces. In Shetland, Hulme and Blyth (1985) reported the detachment and transportation of a dried surface crust, whereas Carling et al. (1997) were experimenting on the smooth bed of a furrow cut into relatively amorphous peat. However, when the surfaces of these furrows were disrupted or scoured by mineral fragments, the peat became more easily eroded. Birnie (1993) found that the surface of peat in Shetland was eroded by between 1 and 3 cm yr^{-1} . The key factor in peat erosion in many areas is the drying of the surface layer which later detaches and can be transported during intense or prolonged rainfall events.

It seems that under natural conditions and without a vegetation cover, organic soils (peats) will be highly erodible, and therefore they will be placed initially in a high risk category. However, there is evidence which suggests that in areas where there is a mixture of organic soils and organo-mineral soils, it is only the organic soils that are eroding (Bibby et al., 1982). This implies that either the organic soils are inherently more erodible than the organo-mineral soils, or some trigger specific to the organic soils is initiating erosion. Clearly further work is needed in this area, but in the meantime, it is proposed that all organic soils (peats) are placed in a high risk category. Those organo-mineral soils designated as 'peaty' or 'humus' will be subject to the same rules regarding slope and runoff as the mineral soils (Table 4).

Table 4: Rank order of potential erodibility for soils with peaty or humus surface layers

Type of organic surface layer	Erosive power						
	a	b	c	d	e	f	g
Peaty or humus topsoil	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*
Organic soils (peats)				*VIII*			

As Tables 3 and 4 show, the various components of slope, runoff and soil texture were combined to produce a ranking of the susceptibility to erosion for mineral soils and those with an organic surface layer.

The overall structure and implementation of the rule base is summarised in Figure 1. This shows how the input data were combined at various stages. Firstly, the slope and runoff were combined to produce an intermediate output of the erosive power of overland flow. This intermediate output was then combined with mineral topsoil textures and with organic topsoils to produce two distinct outputs: erodibility of mineral topsoils and the erodibility of organic topsoils. In order to derive map output of the extent of the geomorphic risk of soil erosion in Scotland, these rules had to be implemented within a GIS using spatial datasets with national coverage.

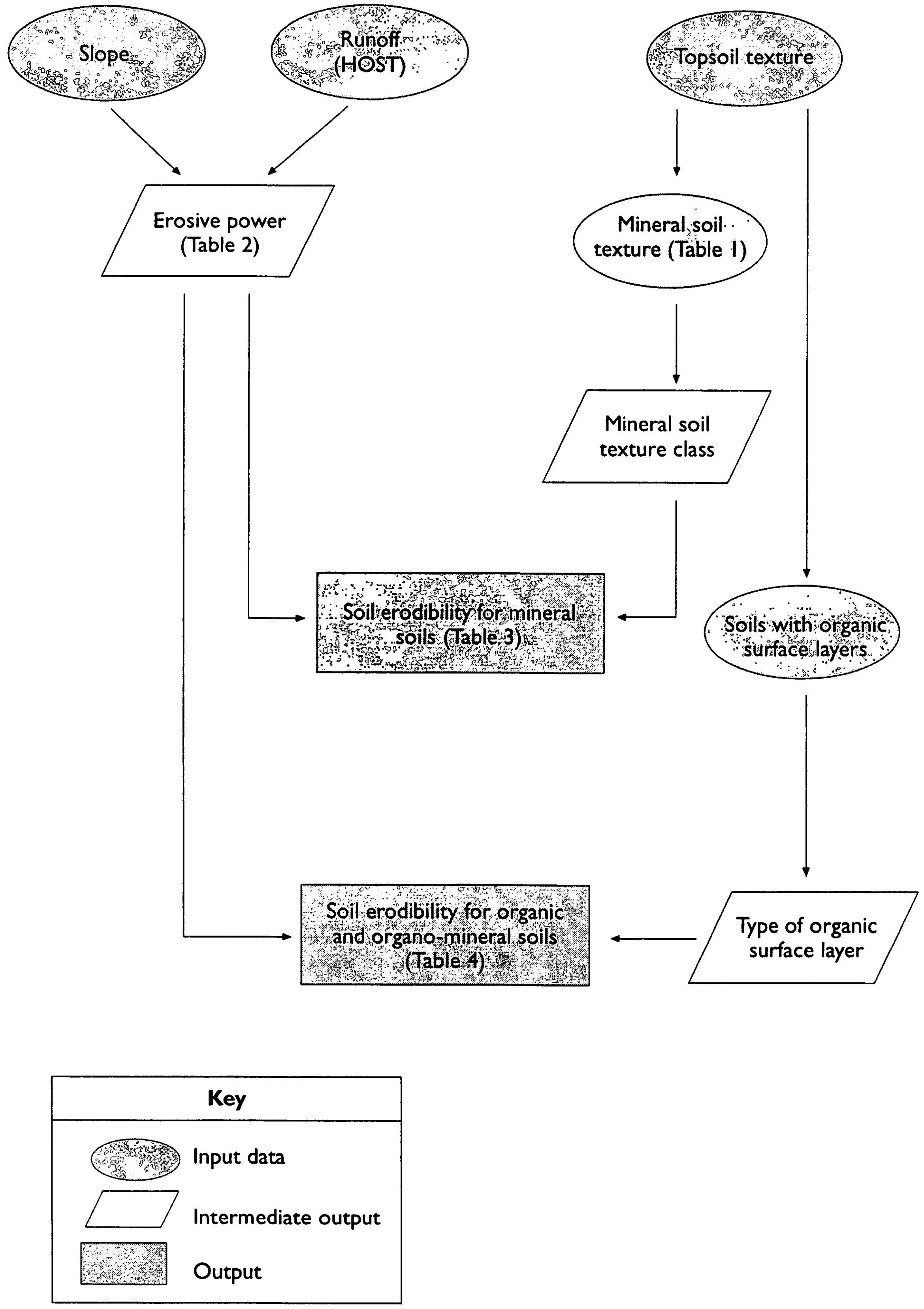
6 SPATIAL DATA

The implementation of the above rules within a GIS involved the recoding and overlay of different spatial datasets. The slope data were calculated from a 50 m resolution Digital Elevation Model (DEM) derived from the Ordnance Survey 1:50 000 scale maps. The soil texture and runoff data were derived from the 1:250 000 scale digital soil map of Scotland. The soil texture class was determined from examination of soil profile descriptions held within the Scottish Soil Database for each Soil Series which occurs on the soil map. The runoff categories were derived from the Hydrology of Soil Types classification (Boorman et al., 1995). Each Soil Series has been allocated to a HOST class and each HOST class has been given a value of Standard Percentage Runoff based on the analysis of the runoff characteristics within 170 catchments. A topsoil texture and a HOST class were then allocated to each Soil series which occurs on the 1:250 000 scale soil map of Scotland.

6.1 Slope

Slopes were calculated from digital elevations which were located on a grid with 50m spacing between grid cells using Horn's method (Horn, 1981) and implemented within the ARC/INFO Geographic Information System. Horn's method was found to perform well in a comparison of eight alternative methods using a grid of digital elevations at 100m intervals for the Isle of Rum (Jones, 1998). The method computed the slope of each individual 50 x 50 m cell using the eight nearest digital elevation cells which were weighted by distance from the cell. Slope was the only topographic factor used in the rule-base. However, further refinements are possible.

Figure 1: Flow chart showing the implementation of the decision rules



In particular, the cumulative flow to each grid cell/land element, weighted by Standard Percent Runoff as calculated from HOST classes, could be determined to give an estimate of the potential throughflow for each cell. Also, an index can be computed for each grid cell, based on grid-cell catchment area divided by elevation gain in the grid-cell catchment. This would give a better estimate of the total cumulative flow passing through each cell. The generated slope angles were grouped into the slope categories shown in Table 1 to produce a slope coverage for Scotland at a resolution of 50 metre grid cells.

6.2 Runoff and soil texture

Both the runoff and soil texture coverages were derived from the digital 1: 250 000 scale National Map of Scotland (MISR, 1981). This digital map comprises around 580 soil map units. These map units are based on landform types, component soils and geological parent material. It is common, therefore, for the soil map unit to have more than one soil type. An important aspect of this spatial dataset is the allied comprehensive attribute database comprising information on the Soil Series within each of these 580 soil map units and their physical condition. Information on Soil Series, topsoil texture, Standard Percentage Runoff (from the HOST dataset) and the proportion of individual Soil Series within each map unit was collated from existing datasets. Following the rules outlined above, the SPR values were grouped into one of three classes, while the soil textures were grouped into 5 categories (three mineral and two organic).

As the map units have more than one soil type, the first stage in using these data was to determine which of the component soils was of greatest extent within each map unit. This was done using information brought together during the development of the HOST classification. Each map unit was examined in turn and both the runoff categories and the texture classes were allocated to the soils within the unit. The runoff/texture class which then constituted the greatest proportion of the map unit was selected to represent that map unit. Where the proportions were evenly divided between soils with mineral and organic surface layers, the mineral soil was chosen to represent that map unit. Where the proportions were evenly divided between soils with organic layers or between soils with mineral layers, the most erodible soil was selected to represent the map unit. It is important to note that by combining the data at this stage, referential integrity was maintained between runoff class and texture class. This would not necessarily have been the case had the datasets been overlaid independently within a GIS where the highest runoff class would have simply been combined with the most potentially erodible soil type despite this combination not occurring in reality. This method of selecting the dominant texture/runoff class means that an allocated erosion class only refers to a proportion of the map unit, the remainder being an estimate of uncertainty in the spatial dataset.

7 IMPLEMENTATION OF RULES WITHIN A GIS

A database of map units with their component soils, their proportions, texture and runoff category was created. By linking these data to the 1: 250 000 scale soil map, coverages of dominant runoff and texture were made. Following the rules described

above, the runoff coverage was then overlain onto the slope coverage to derive an erosive power map. This map was then combined with the soil surface texture coverage to derive an erodibility map with numerous categories (Figure 2). These categories were then grouped into mineral soils with a low, moderate or high risk of erosion occurring and into those soils with organic surface layers with low moderate or high risk (Table 5 and Table 6). As the classification deals with the inherent geomorphological risk of erosion, there is a probability of the occurrence of erosion in all risk categories. The probability is lowest in the low risk categories but, never the less, there remains a risk even within these classes. The final raster map output, with a resolution of 50 m, is of the inherent geomorphic risk of soil erosion by overland flow in Scottish soils.

As only the erosive power class which constituted the greatest proportion of a map unit can be shown on the map, there can be a great deal of uncertainty associated with the map output. In general, the 'worst case' (that is, the most erodible category) has been selected to represent a map unit where the proportion of soil types and runoff categories was evenly divided. However, this information is retained with the database and could be used to derive mapped estimates of the uncertainty. This limitation to the precision of the final map output implies that it should be used only to give a broad indication of the potential for soil erosion to occur in an area.

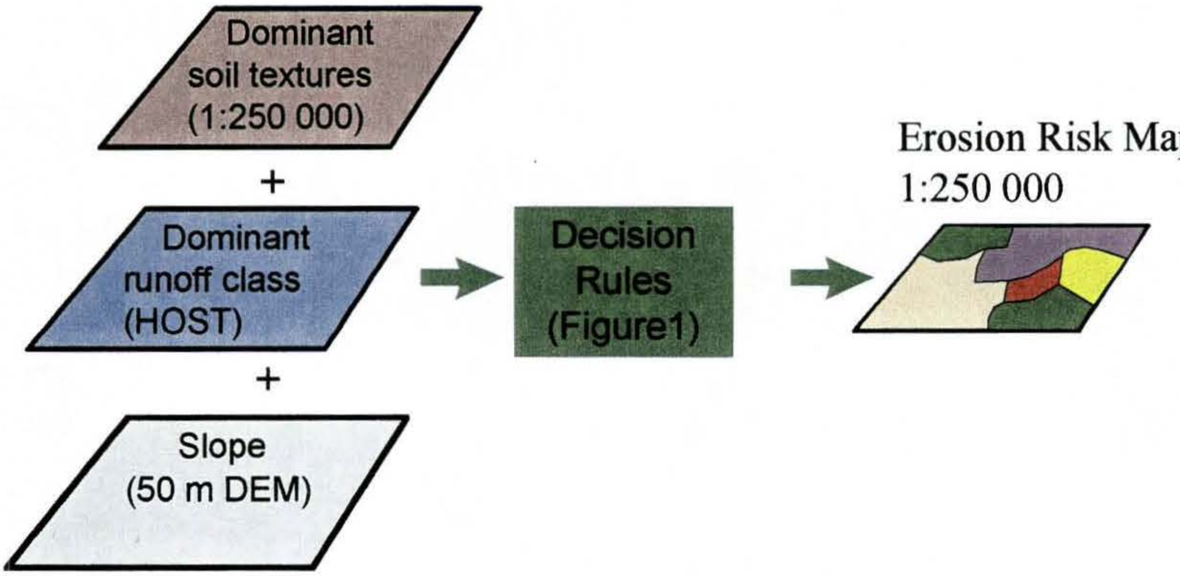
Table 5. Erodibility classes for mineral soils

Soil texture class	Erosive power						
	a	b	c	d	e	f	g
Fine	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Medium	*2*	***Low***	*4*	***Moderate***	*6*	***High***	*8*
Coarse	*3*	*4*	*5*	*6*	*7*	*8*	*9*

Table 6: Erodibility classes for soils with peaty or organic surface layers

Type of organic surface layer	Erosive power						
	a	b	c	d	e	f	g
Peaty or humus topsoil	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*
		Low			***Moderate***		
Organic soils (peats)				***High***	*VIII*		

Figure 2: Overlay of spatial data



8 SUMMARY STATISTICS AND COMMENTS

The areas and proportions of the different erodibility classes that occur in each of the 21 areas within SNH's framework for Natural Heritage Futures were determined along with a National summary. These figures represent the proportion of land area within each area only and do not include areas of fresh and inland water bodies.

8.1 National

Some scale-related error is inevitable when determining the proportion of land in each erosion class from map data. This error will be exacerbated as only the dominant soil texture/runoff class was selected as representative of the soil map units. In order to assess this additional error, the proportion of soils with organic and with mineral topsoils was calculated from the erosion risk map data. Approximately 52% of the land area had soils with organic surface layers and about 44 % had mineral topsoils. The remainder comprised a miscellaneous group of bare rock or scree, built-up area and unstable slopes. These figures were then compared to those calculated from the attribute table linked to the 1:250 000 scale digital soil map which has estimates of the proportions of individual soil types within each map unit. Determined in this way, the proportion of soils with organic topsoils was 53.4%, while 46.6% had mineral topsoils. Since these figures do not have an estimate of built-up area or of unstable slopes, a direct comparison between the two sets of figures cannot be made, but their similarity suggests that no systematic bias has been introduced into the National statistical summary. However, this may not hold within each individual area.

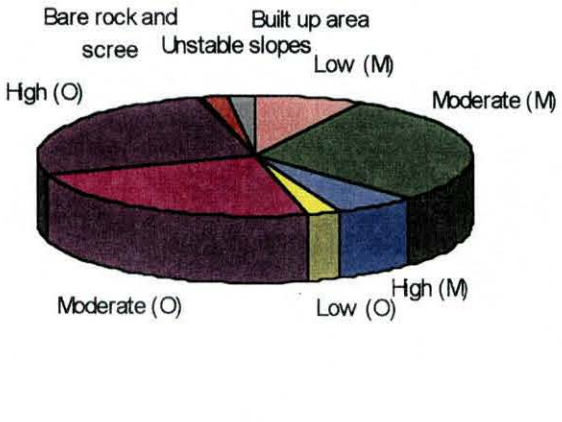
In terms of the inherent geomorphic risk of soil erosion by overland flow, the greatest proportion of mineral soils falls into the moderate risk category. The soils with organic surface layers, however, fall primarily into the moderate and high risk

categories, with only a very small proportion in the low risk category. When unvegetated, the organic layers are very susceptible to erosion and, as they are often found in upland areas, the slopes on which these soils develop can be steep. It should be remembered that the risk categories for mineral soils and for soils with organic surface layers are not comparable; rather they represent two distinct rankings. Approximately 2% of Scotland was classified as having inherently unstable slopes where overland flow, will not necessarily be the dominant erosion process. These slopes will also be subject to soil creep or other mass movements despite being vegetated. The areas of bare rock and scree have been taken directly from the 1:250 000 soil map. The bare rock component of this unit has no surface texture and is resistant to erosion by overland flow, while the scree is likely to be sufficiently permeable to deter the development of overland flow. Due to the assumptions made during the development of this classification, even land in the low risk category will have some chance of being eroded.

Table 7. National summary

Category	Erosion risk	Percentage of Scotland	Actual area (ha)
Mineral (43.7%)	Low	8.0	618778
	Moderate	29.6	2275497
	High	6.1	469086
Organic (52.3%)	Low	2.5	193127
	Moderate	23.8	1830402
	High	26.0	1997975
Miscellaneous (4.0%)	Bare rock and scree	0.3	23858
	Unstable slopes	1.9	147792
	Built Up Area	1.8	142286

Figure 3: Proportion of Scotland in each erosion class



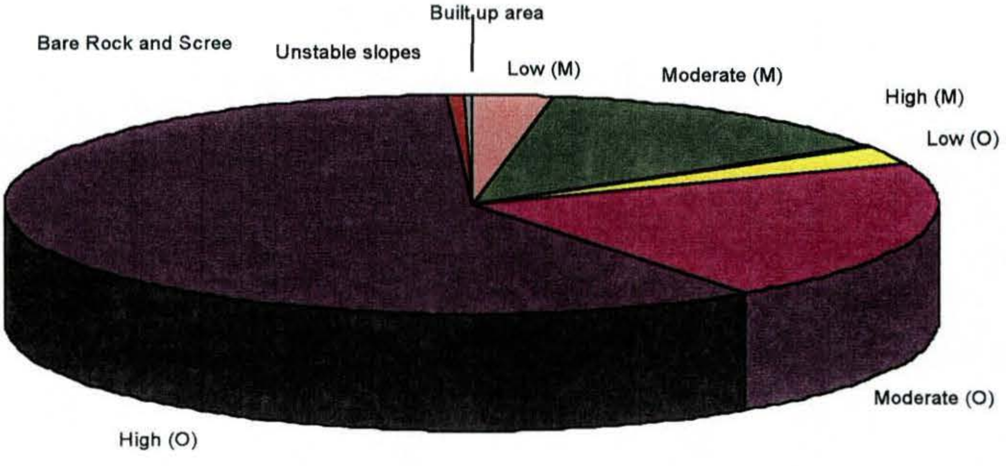
8.2 Shetland

In Shetland, the soils are dominated by those with organic surface layers and peats and have a large proportion of land in the moderate and high risk categories. It was in Shetland that Hulme and Blyth (1985) observed extensive peat erosion on gentle slopes during an intense rainfall event. Birnie (1993) noted that the peatland of Shetland is actively eroding and, earlier, Birnie and Hulme (1990) suggested that this was largely due to overgrazing which reduces the vegetation cover. Only 16.5% of the islands is covered by the categories for mineral soils and, of these, a moderate erosion risk is by far the most prevalent.

Table 8. Shetland

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	2.9	4046
	Moderate	13.3	18628
	High	0.3	392
Organic	Low	2.5	3487
	Moderate	21.1	29453
	High	59.0	82605
Miscellaneous	Bare rock and scree	0.1	195
	Unstable slopes	0.5	641
	Built Up Area	0.3	440

Figure 4: Proportion of Shetland in each erosion class



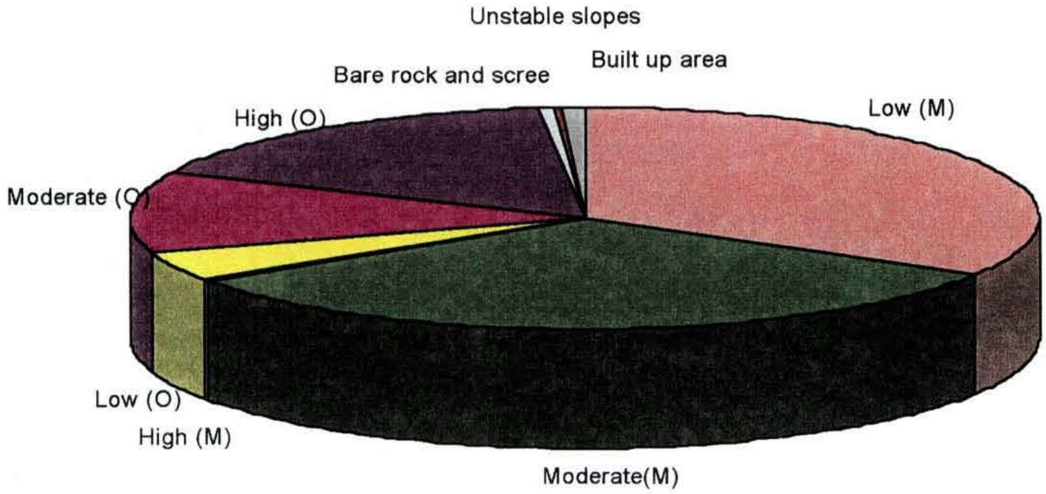
8.3 Pentland and Orkney

In contrast to Shetland, Orkney has a significant proportion of mineral soils (although this also includes the arable areas of Caithness). The erosion risk for the areas of mineral soils is low to moderate, which is probably a reflection of the gently undulating landscape. Hoy, parts of Orkney Mainland and parts of Caithness are of predominantly organic and organo-mineral soils and around 19% of this area has been classified as having a moderate to high risk on these soil types. The high risk soils are mainly deep blanket peats.

Table 9: Pentland and Orkney

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	33.7	55565
	Moderate	32.1	52957
	High	0.5	801
Organic	Low	4.0	6571
	Moderate	12.1	19876
	High	16.6	27347
Miscellaneous	Bare rock and scree	< 0.1	63
	Unstable slopes	0.3	446
	Built Up Area	0.7	1168

Figure 5: Proportion of Pentland and Orkney in each erosion class



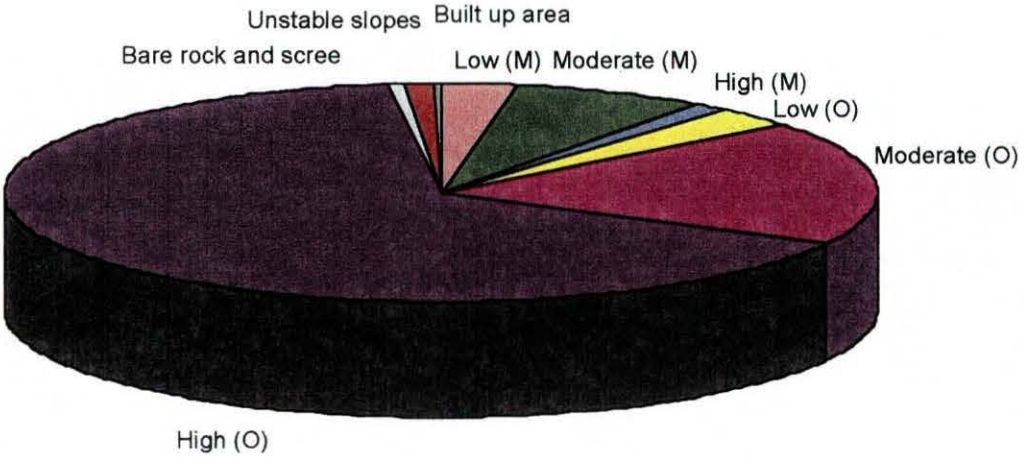
8.4 Western Isles

The Western Isles are dominated by peats and by peaty soils on steep slopes, which explains why over 65% of this area has a high erosion risk for organic soils. The small area of mineral soils falls largely within the moderate risk class and is generally confined to the coarse textured soils of the western coastal fringe and the island of Tiree. The island of Coll is classified primarily as have low risk soils with organic surface layers.

Table 10: Western Isles

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	2.7	8105
	Moderate	7.3	21814
	High	1.4	4185
Organic	Low	2.6	7736
	Moderate	18.8	55861
	High	65.2	193928
Miscellaneous	Bare rock and scree	0.5	1401
	Unstable slopes	1.3	3796
	Built Up Area	0.2	460

Figure 6: Proportion of Western Isles in each erosion class



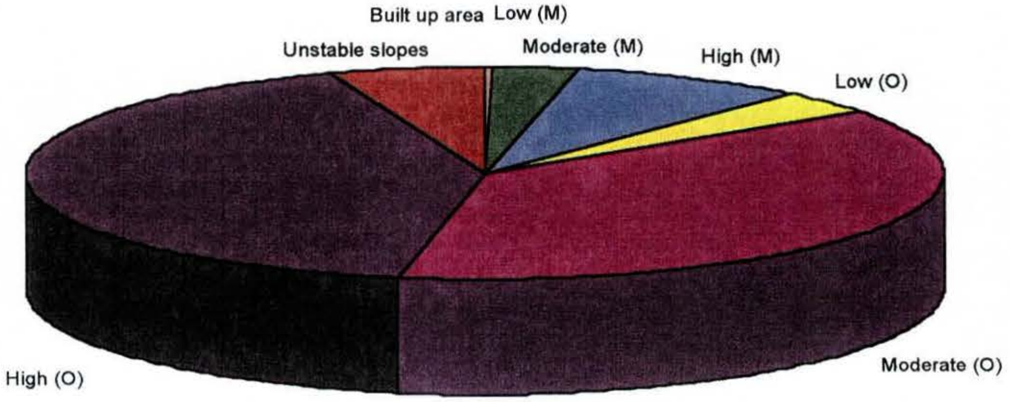
8.5 North West Seaboard

The North West Seaboard of Scotland also has a high proportion of organic and organo-mineral soils and, as a consequence, has around 80% of land in the moderate to high erosion risk classes for organic soils. This area has extensive areas of blanket peat which occurs as a single soil type over large areas and as a major component of complex soil patterns in association with peaty gleys, peaty podzols and peaty rankers. A high proportion of steep slopes in this area means that both mineral and organo-mineral soils are likely to be at a high risk of eroding. The percentage cover of unstable slopes in this area is significantly greater than the national average.

Table 11. North West Seaboard

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	0.3	906
	Moderate	3.1	10563
	High	8.3	28693
Organic	Low	3.5	12087
	Moderate	37.8	130243
	High	41.5	143004
Miscellaneous	Bare rock and scree	0	0
	Unstable slopes	5.4	18604
	Built Up Area	< 0.1	125

Figure 7: Proportion of North West Seaboard in each erosion class



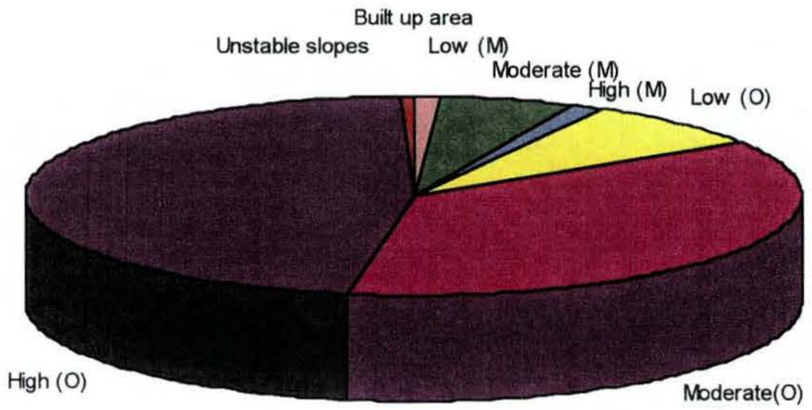
8.6 The Flow Country

The Flow Country is dominated by extensive areas of organic soils and of soils with organic surface layers on steep slopes. Mineral soils make up only 8% of the area. The true 'Flow Bog' to the east of the area and the remaining areas of blanket peat have been classified as having a high risk of erosion, while the areas where the soils have organic surface layers range from low to high risk, depending on the slope of the land and the percentage runoff. In general, however, these soils primarily fall into the moderate erosion risk category.

Table 12: The Flow Country

Category	Erosion risk	Percentage of area	Actual area (ha)
	Low	1.2	6190
Mineral	Moderate	5.4	27204
	High	1.4	7190
	Low	7.8	39374
Organic	Moderate	36.8	185646
	High	46.9	236184
	Bare rock and scree	0	0
Miscellaneous	Unstable slopes	0.4	2207
	Built Up Area	0.1	347

Figure 8: Proportion of The Flow Country in each erosion class



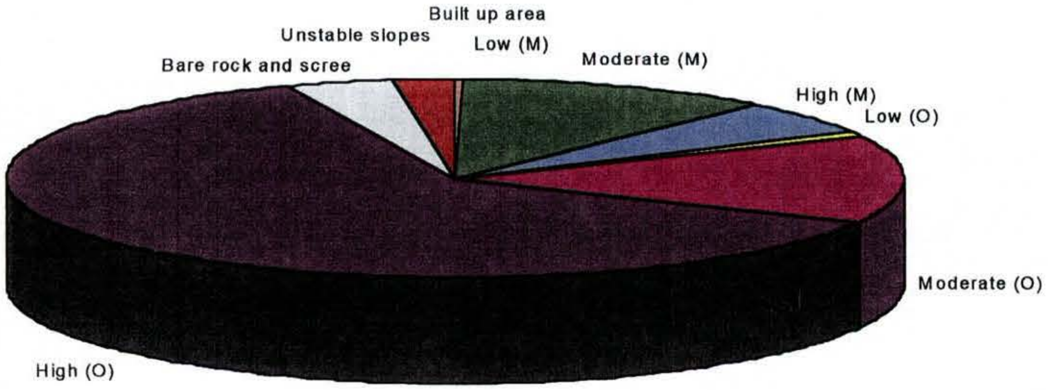
8.7 Western Seaboard

The Western Seaboard comprises primarily the islands of Mull and Skye and the peninsula of Ardnamurchan. The soil map shows the Islands of Skye and Mull are dominated by map units which comprise 50% peat soils and 50% organo-mineral soils. Given the decision to represent the 'worst case' on the erosion risk map where there are equal proportions of differently classified soils, this means that large tracts of the islands have been classed as having a high risk of erosion. Within this area, the proportion of bare rock and scree is much greater than the national average. Areas such as the Cuillin have very little soil development and so comprise bare rock and screes. Such areas were unclassifiable using the decision rules. However, rock should be taken as not erodible by overland flow, while the screes (although still active) will also not be susceptible to erosion by overland flow, due to their high permeability.

Table 13: Western Seaboard

Category	Erosion risk	Percentage of area	Actual area (ha)
	Low	0.3	994
Mineral	Moderate	11.4	34674
	High	5.5	16836
	Low	0.8	2341
Organic	Moderate	14.3	43489
	High	61.6	187843
	Bare rock and scree	4.0	12158
Miscellaneous	Unstable slopes	2.0	6185
	Built Up Area	0.1	372

Figure 9: Proportion of Western Seaboard in each erosion class



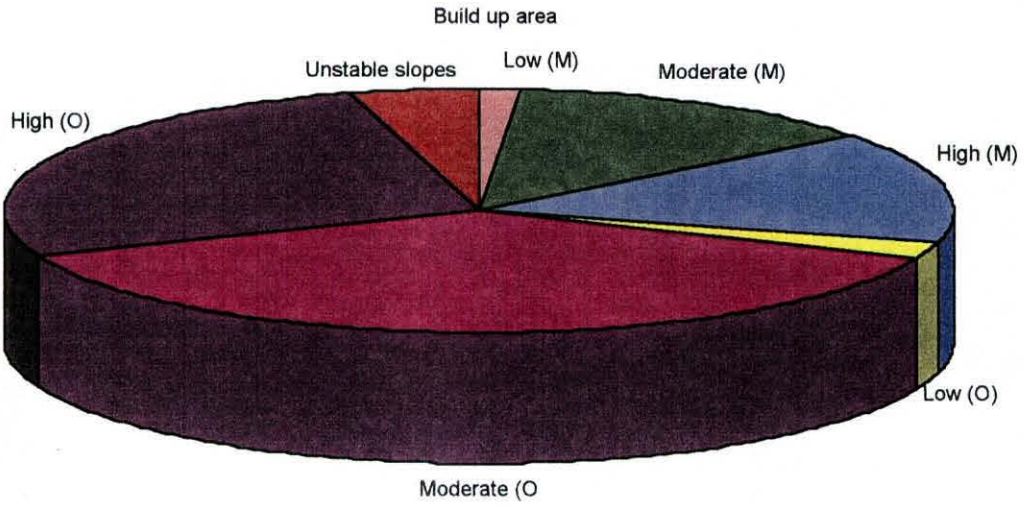
8.8 Northern Highlands

Dominated by organo-mineral soils, the Northern Highlands has over 60% of its land area in either the high or moderate erosion risk class for soils with organic surface layers. Steep slopes and high runoff potentials contribute to the higher erosion risks in this area. No areas of bare rock and scree were mapped at 1: 250 000 scale in this area which does not imply that these features do not exist. Instead, they will have been incorporated into the soil map units as minor components.

Table 14: Northern Highlands

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	1.3	6888
	Moderate	13.1	69043
	High	14.8	77920
Organic	Low	2.3	11933
	Moderate	37.3	196532
	High	26.7	140848
Miscellaneous	Bare rock and scree	0	0
	Unstable slopes	4.5	23625
	Built Up Area	< 0.1	140

Figure 10: Proportion of Northern Highlands in each erosion class



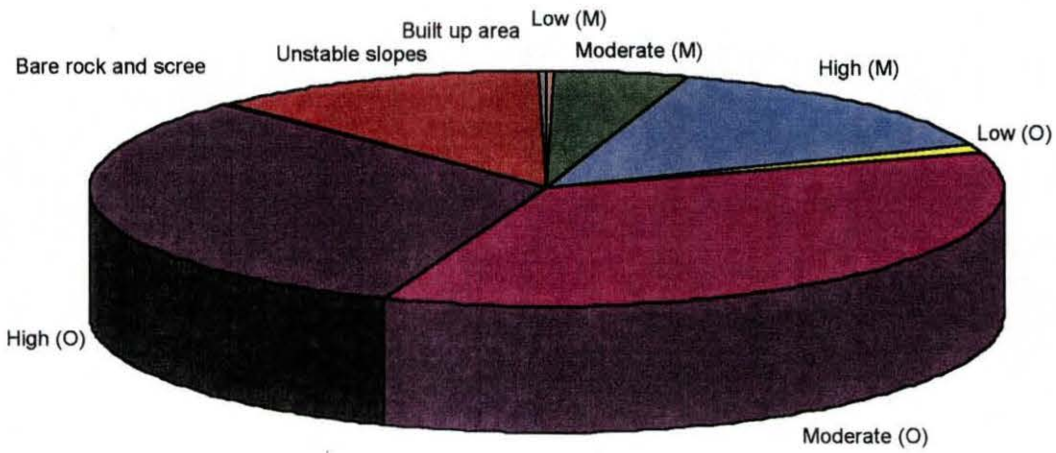
8.9 Western Highlands

The Western Highlands is dominated by organo-mineral soils, steep slopes and high runoff potentials, hence the large areas of land with a moderate to high risk of erosion. The area of unstable slopes is significantly above the national average.

Table 15: Western Highlands

Category	Erosion risk	Percentage of area	Actual area (ha)
	Low	0.4	1041
Mineral	Moderate	4.7	12071
	High	13.7	34958
	Low	1.2	2945
Organic	Moderate	36.0	91895
	High	31.6	80713
	Bare rock and scree	0.3	793
Miscellaneous	Unstable slopes	11.9	30401
	Built Up Area	0.2	589

Figure 11: Proportion of Western Highlands in each erosion class



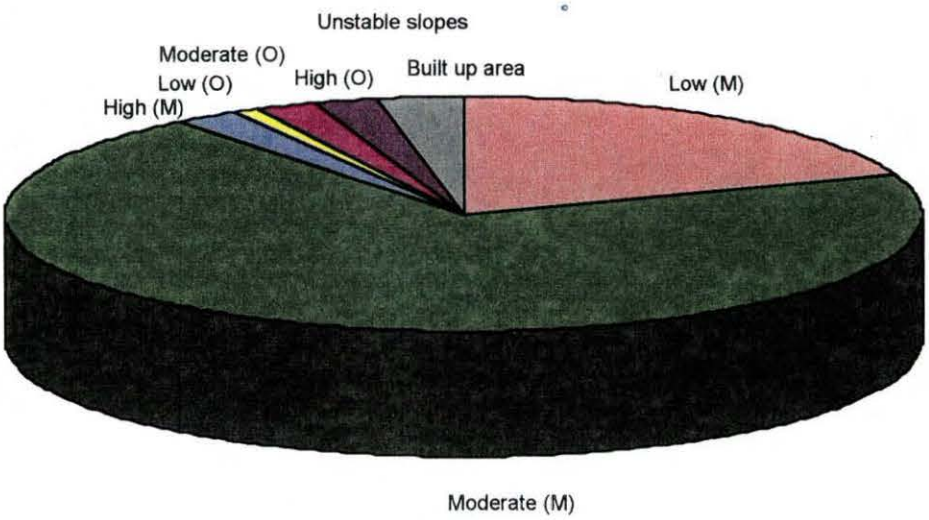
8.10 North East Coastal Plain

The North East Coastal Plain is dominated by mineral soils. This part of Scotland has a rolling landscape with gentle to moderately steep slopes. Many of the soils have an intermediate runoff potential and coarse to medium textured topsoils. There is considerable anecdotal evidence for erosion of mineral soils in response to heavy or prolonged rainfall and in 1991, Watson and Evans reported instances of erosion in some arable fields in this area. The small areas of basin peats have been classified as having a high risk within the organic category.

Table 16: North East Coastal Plain

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	19.6	63019
	Moderate	69.9	225225
	High	2.1	6603
Organic	Low	0.9	2985
	Moderate	2.3	7295
	High	2.2	7087
Miscellaneous	Bare rock and scree	0	0
	Unstable slopes	< 0.1	26
	Built Up Area	3.0	9629

Figure 12: Proportion of North East Coastal Plain in each erosion class



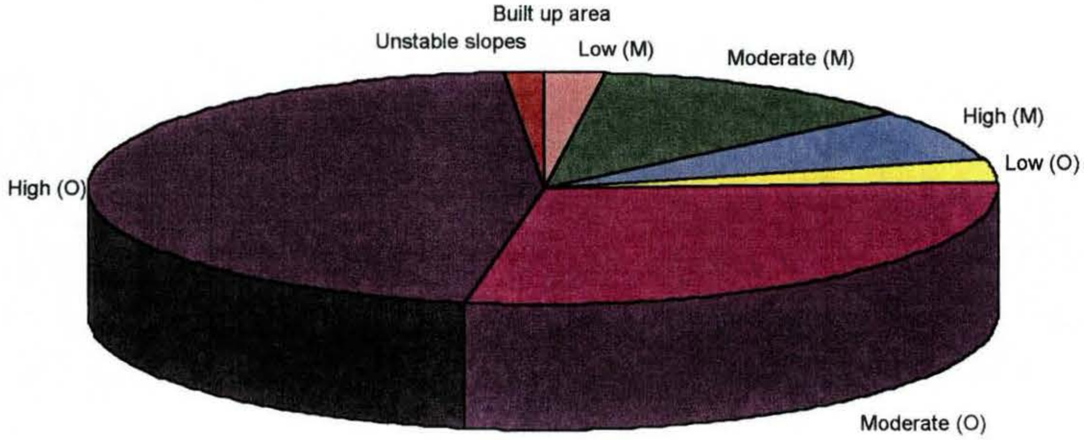
8.11 Central Highlands

Lying between the Spey and the Great Glen, the Central Highlands has a high proportion of organic soils (deep peats) which already show substantial erosion. These peats occur primarily on the Monadhliath Mountains. To the south west of the area, the soils are largely organo-mineral and have a moderate risk of erosion. At low altitudes and along the valley sides, the soils are more mineral in nature and have been classified mainly as having a moderate to high risk of erosion.

Table 17: Central Highlands

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	2.1	5652
	Moderate	11.8	31922
	High	7.3	19658
Organic	Low	3.0	8104
	Moderate	28.7	77534
	High	45.8	123765
Miscellaneous	Bare rock and scree	0	0
	Unstable slopes	1.3	3515
	Built Up Area	< 0.1	34

Figure 13: Proportion of Central Highlands in each erosion class



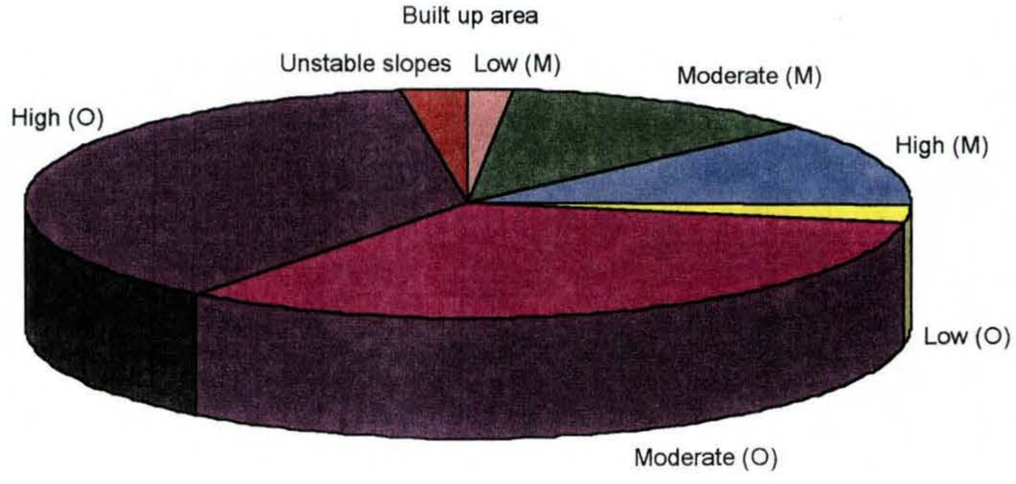
8.12 Cairngorm Massif

The high tops of the Cairngorms are a complex mixture of bare rock, mineral and organo-mineral soils. The soils are subject to freeze/thaw processes which give rise to a loose, porous soil which is highly permeable. The constant mixing by these processes often results in a highly organic, though mineral, topsoil. In winter, these soils become frozen and are then impermeable, making the prediction of a suitable percentage runoff value for these soils difficult. To the south of the region, the mountain tops are at lower altitudes and are dominated by blanket peats (organic soils) which have a high erosion risk.

Table 18: Cairngorm Massif

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	1.6	6589
	Moderate	11.7	47189
	High	12.0	48056
Organic	Low	2.5	10137
	Moderate	32.6	131080
	High	37.0	148593
Miscellaneous	Bare rock and scree	0	0
	Unstable slopes	2.6	10369
	Built Up Area	< 0.1	40

Figure 14: Proportion of Cairngorm Massif in each erosion class



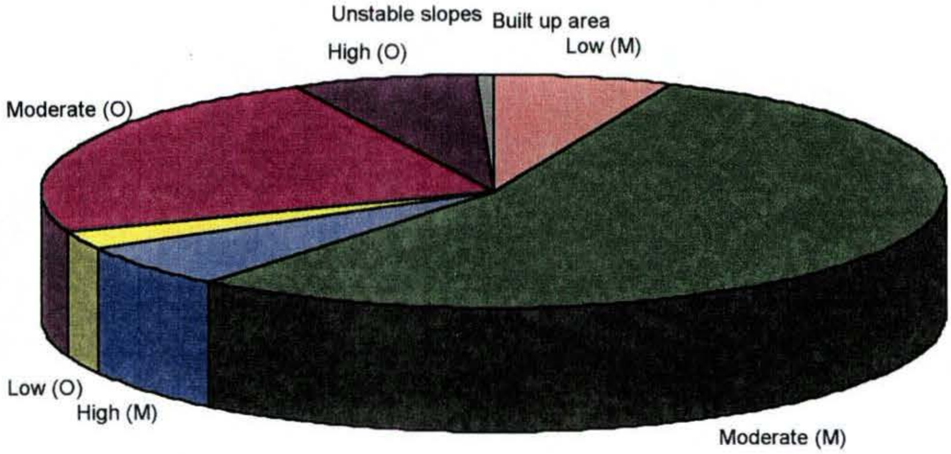
8.13 North East Glens

The North East Glens mainly comprises mineral soils with a moderate erosion risk. The slopes are gentle to moderately steep in the main. At higher altitudes, the soils have organic surface layers and, together with higher runoff potentials and steeper slopes, means that they are mainly in the moderate erosion risk class for the organic category.

Table 19: North East Glens

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	6.3	23489
	Moderate	54.4	204621
	High	6.2	23269
Organic	Low	2.5	9238
	Moderate	23.3	87364
	High	6.7	25267
Miscellaneous	Bare rock and scree	0	0
	Unstable slopes	0.1	527
	Built Up Area	0.5	1727

Figure 15: Proportion of North East Glens in each erosion class



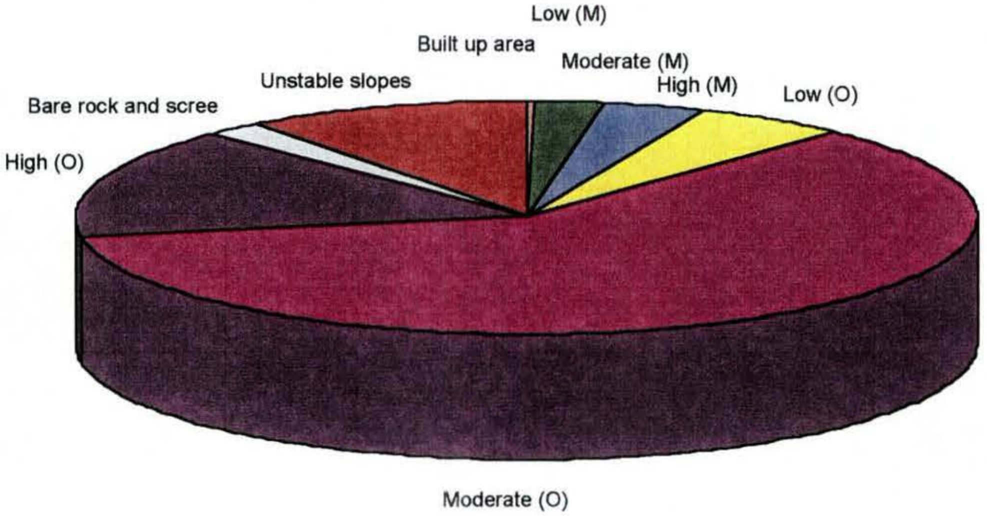
8.14 Lochaber

In common with much of North and West Scotland, Lochaber is dominated by organo-mineral soils, which, when combined with steep slopes and high runoff potentials, gives rise to large areas of land with organic surface layers having a moderate risk of erosion. The percentage cover of unstable slopes is also significantly above the national average.

Table 20: Lochaber

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	0.4	887
	Moderate	2.5	5887
	High	3.5	8275
Organic	Low	5.6	13235
	Moderate	60.6	142880
	High	15.2	35928
Miscellaneous	Bare rock and scree	2.0	4772
	Unstable slopes	10.1	23838
	Built Up Area	0.1	165

Figure 16: Proportion of Lochaber in each erosion class



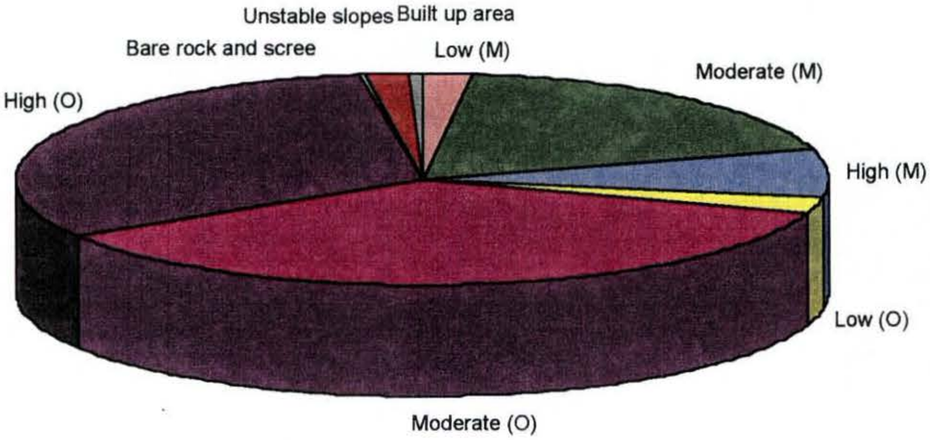
8.15 Argyll West and Islands

The Argyll West and Islands comprises part of the Scottish mainland to the north of the Firth of Clyde, the Kintyre Peninsula and the islands of Arran, Islay and Jura. Despite being in the wetter west of Scotland, over 25% of the land area comprises mineral soils with a moderate to high erosion risk. However, over 66% of the land has the equivalent erosion risk classes with organic surface layers.

Table 21: Argyll West and Islands

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	1.9	9569
	Moderate	18.6	94297
	High	7.1	36085
Organic	Low	2.6	13274
	Moderate	36.0	181764
	High	31.2	157544
Miscellaneous	Bare rock and scree	0.5	2534
	Unstable slopes	1.4	7141
	Built Up Area	0.7	3462

Figure 17: Proportion of Argyll West and Islands in each erosion class



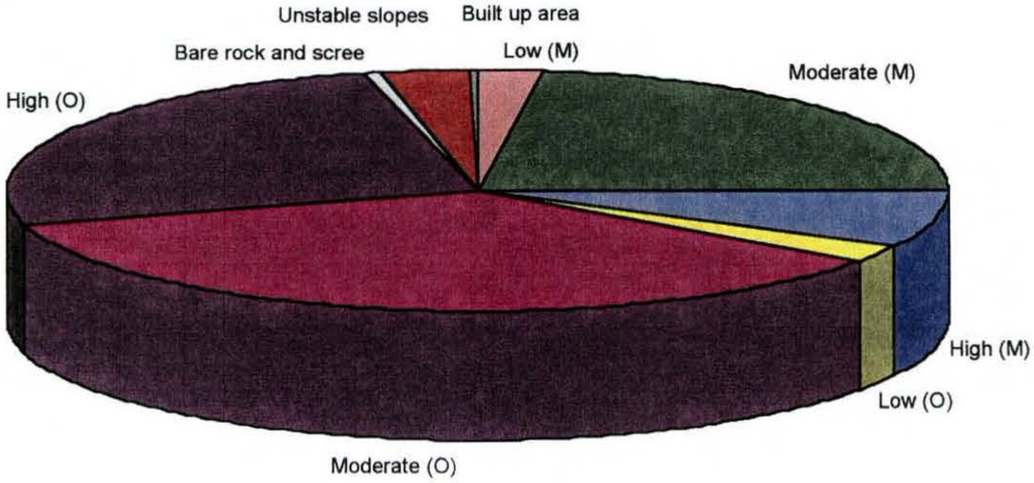
8.16 Central Argyll and Breadalbane

The uplands of Central Argyll and Breadalbane are dominated by organo-mineral soils, while the lowlands have a high proportion of mineral soils. However, these lower elevation slopes are often moderately steep to steep, with a consequence that the mineral soils have a moderate or high risk or erosion.

Table 22: *Central Argyll and Breadalbane*

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	2.1	7231
	Moderate	22.9	77850
	High	7.6	25879
Organic	Low	2.3	7899
	Moderate	35.5	120395
	High	25.7	87318
Miscellaneous	Bare rock and scree	0.6	1864
	Unstable slopes	3.0	10232
	Built Up Area	0.3	835

Figure 18: Proportion of Central Argyll and Breadalbane in each erosion class



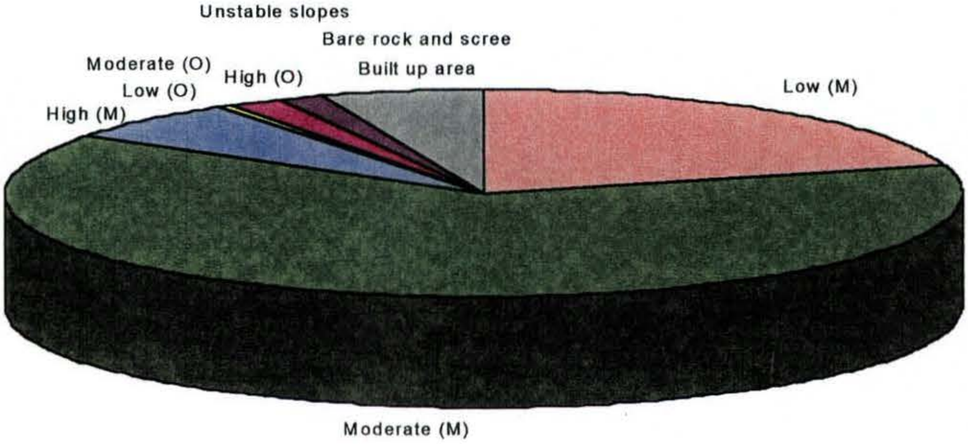
8.17 Eastern Lowlands

The Eastern Lowlands encompasses the arable land south and east of the Highland Boundary Fault to the English border. Within this region, there is considerable documented evidence of severe but localised erosion of mineral soils on arable land (for example, Davidson and Harrison,1995; Kirkbride and Reeves, 1993; Wade and Kirkbride, 1998; Watson and Evans, 1991; Spiers and Frost, 1985; Frost and Spiers,1996). The vast majority of the land falls into either a low risk (permeable soils on gentle slopes) or a moderate risk (less permeable soils on more steeply sloping land) with localised areas of high risk. This apparent contradiction perhaps highlights the role of management in inducing erosion on soils which are, seemingly, at only moderate risk especially when compared with the figures for the West Central Belt. The majority of these erosion events were recorded in arable fields.

Table 23. Eastern Lowlands

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	20.5	174993
	Moderate	63.9	546095
	High	6.1	52620
Organic	Low	0.7	6042
	Moderate	1.8	15246
	High	1.4	11702
Miscellaneous	Bare rock and scree	< 0.1	31
	Unstable slopes	0.1	878
	Built Up Area	5.5	47009

Figure 19: Proportion of Eastern Lowlands in each erosion class



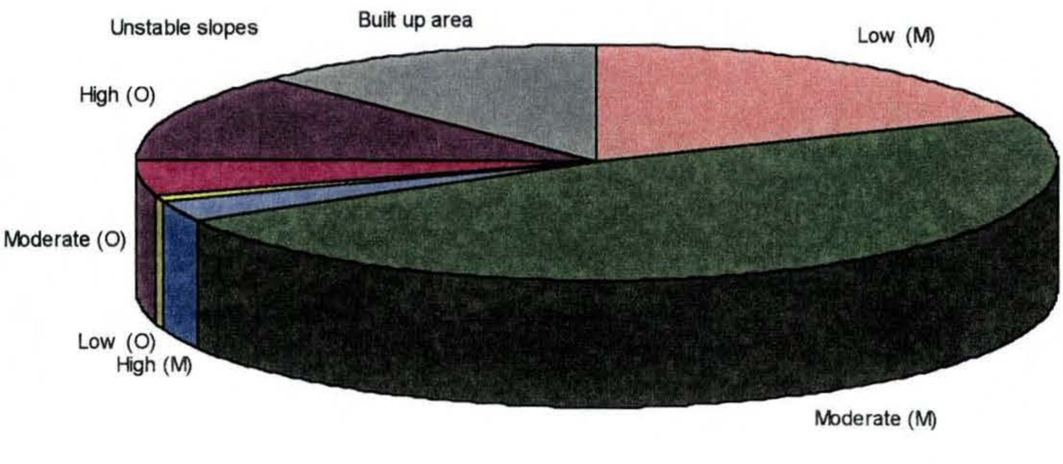
8.18 West Central Belt

The relative proportions of erosion classes amongst the mineral soils for the West Central Belt do not differ markedly from those of the Eastern Lowlands, yet the incidences of soil erosion are much less in the wetter west than in the east of Scotland. This area is dominated by pasture rather than arable agriculture. However, the indications are that, under conditions devoid of vegetation, these low permeability soils would be moderately susceptible to erosion. More detailed analysis (not presented here) shows the mineral soils in the West Central Belt to have a slightly lower ranking than those in the East Lowlands.

Table 24: West Central Belt

Category	Erosion risk	Percentage of area	Actual area (ha)
	Low	18.6	95213
Mineral	Moderate	48.1	245799
	High	2.9	14556
	Low	0.8	3964
Organic	Moderate	5.0	25400
	High	12.1	61811
	Bare rock and scree	0	0
Miscellaneous	Unstable slopes	< 0.1	371
	Built Up Area	12.5	63882

Figure 20: Proportion of West Central Belt in each erosion class



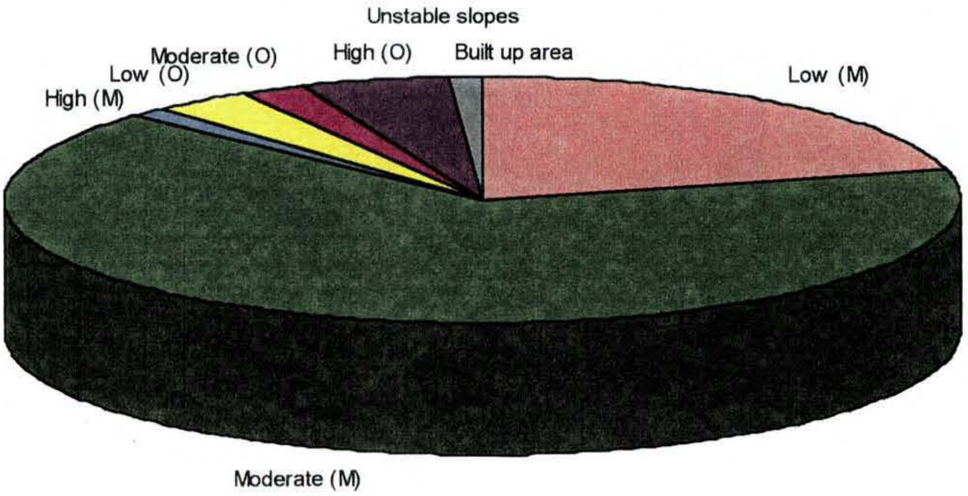
8.19 Wigtown Machairs and Solway Coast

The Wigtown Machairs and Solway Coast is one of the smallest areas. Being predominantly lowland, over 85% of the area falls into the mineral soil erosion risk category with a low to moderate risk.

Table 25: Wigtown Machairs and Solway Coast

Category	Erosion risk	Percentage of area	Actual area (ha)
	Low	21.2	15790
Mineral	Moderate	65.8	48927
	High	1.5	1124
	Low	3.2	2358
Organic	Moderate	2.4	1814
	High	4.9	3645
	Bare rock and scree	0	0
Miscellaneous	Unstable slopes	<0.1	58
	Built Up Area	1.0	773

Figure 21: Proportion of Wigtown Machairs and Solway Coast in each erosion class



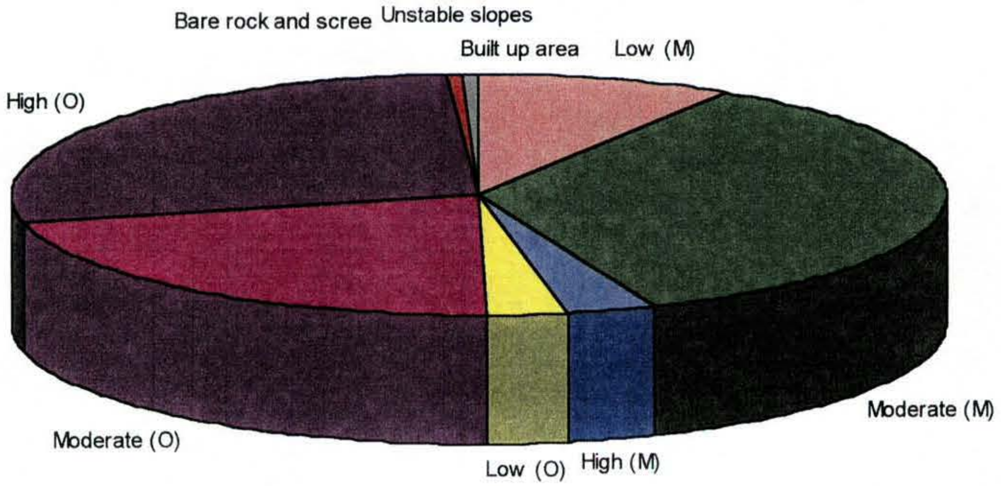
8.20 Dumfries and Galloway

The Dumfries and Galloway comprises approximately 50% of soils in the mineral erosion risk category and 50% in the organic reflecting the contrast between the lowlands and uplands. A high proportion of the uplands is in the high erosion risk class as the soils have been mapped either as blanket peat or as complex map units with more than 50% peat.

Table 26: Dumfries and Galloway

Category	Erosion risk	Percentage of area	Actual area (ha)
	Low	8.9	58992
Mineral	Moderate	35.0	232152
	High	3.1	20604
	Low	2.7	17669
Organic	Moderate	21.7	144095
	High	27.6	183524
	Bare rock and scree	< 0.1	47
Miscellaneous	Unstable slopes	0.3	2045
	Built Up Area	0.7	4464

Figure 22: Proportion of Dumfries and Galloway in each erosion class



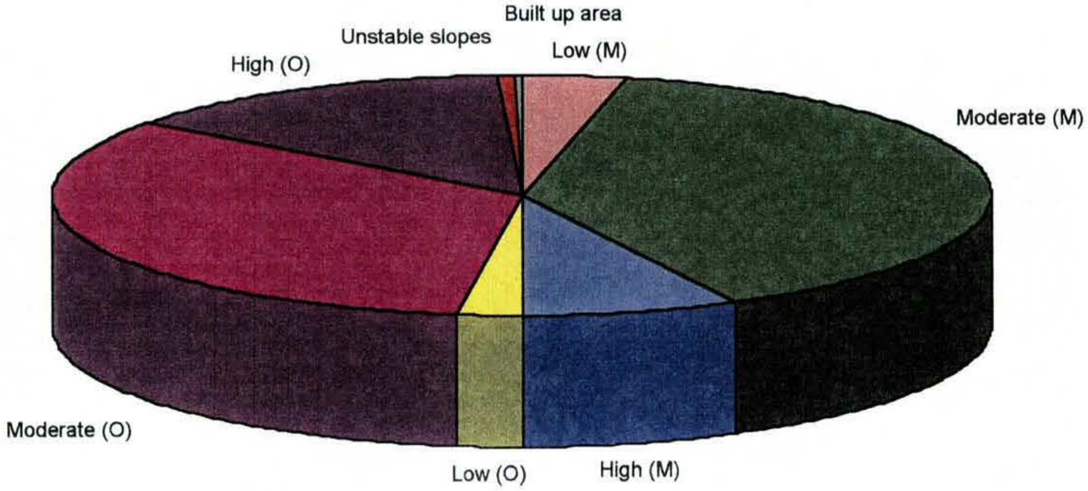
8.21 Border Hills

Despite being a predominantly upland area, the Border Hills has a high proportion of mineral soils. These soils are largely brown earths which occur on the steeper slopes. Although the soils are quite permeable, the steepness of the slopes and moderate runoff combine to put these soils into the moderate risk class.

Table 27: Border Hills

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	3.7	15373
	Moderate	38.8	159272
	High	7.6	31054
Organic	Low	2.2	9033
	Moderate	33.2	136456
	High	13.7	56464
Miscellaneous	Bare rock and scree	0	0
	Unstable slopes	0.6	2620
	Built Up Area	0.2	1001

Figure 23: Proportion of Border Hills in each erosion class



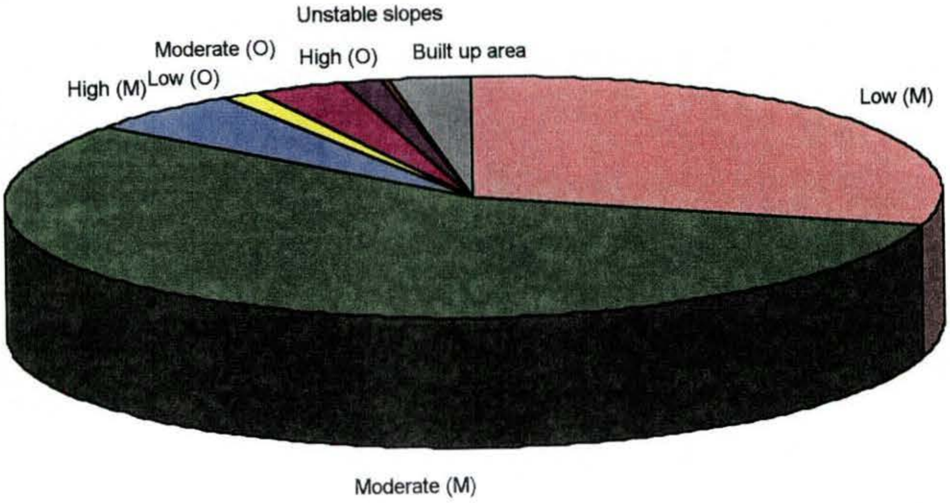
8.22 Moray Firth

The Moray Firth is dominated by mineral soils. These permeable soils occur on fairly gentle slopes and fall into the low to moderate erosion classes. The area is noted for its high incidence of soil erosion by wind. However, this form of soil erosion was not part of this study and is not shown on the map.

Table 28: Moray Firth

Category	Erosion risk	Percentage of area	Actual area (ha)
Mineral	Low	29.8	58246
	Moderate	55.9	109307
	High	5.3	10328
Organic	Low	1.4	2715
	Moderate	3.1	6084
	High	1.5	2855
Miscellaneous	Bare rock and scree	0	0
	Unstable slopes	0.1	267
	Built Up Area	2.9	5624

Figure 24: Proportion of Moray Firth in each erosion class



9 VALIDATION

Within the terms of reference for this project there was little scope for validation of the rules. As there was no experimentation, validation of the rules and output can only be made by expert opinion or by comparison of the results with areas where erosion has occurred. This latter option is not wholly satisfactory as there are many other factors which inhibit the expression of the inherent geomorphological erosion risk such as the presence of a vegetation cover. However, the map output has indicated that there is an elevated risk of soil erosion in many of the areas where there is documentary evidence of soil erosion occurring, for example, in Shetland and in the Eastern Lowlands. Overall, there are few areas in Scotland where there is a low risk of soil erosion given the right set of circumstances, and therefore the role of management and the vegetation cover in protecting the soil resource is critical.

10 MODEL SENSITIVITY

Any model is sensitive to some or all of its parameters and a sensitivity analysis should be an integral part of the development and implementation of any new model or rule-base. However, within the current project only a qualitative assessment of the model sensitivity could be made.

The model has three major components: topography, runoff and soils, each with their own set of sensitivities. The first was represented solely by slope. It was surprisingly difficult to fix a set of meaningful slope categories. The USLE does not divorce slope angle from slope length, and so it was not possible to use the slope categories from this work. Other erosion prediction schemes appeared to use arbitrary limits with an arithmetic progression (for example, the CORINE study - Briggs and Giordano, 1992). The slope categories finally selected for use in this study reflect the angles found in the landscape in response to significant geomorphological processes. These categories then represent natural breaks in the continuum of slope angles. Clearly there is still the issue of categorising continuous data and the possibility of setting the wrong limits. As the slope angle is then combined with the runoff potential, the generated parameter of *Erosive power* covers a wide range of slope angles, which may well reduce the overall sensitivity of the model to slope. In this rule-base, slopes greater than 30^{0} were considered to be unstable and likely to be actively eroding even under conditions of little runoff. However, slope instability is a function of slope angle and the cohesiveness of the drift deposit, which varies. Therefore, different drift deposits will have different critical angles beyond which they are inherently unstable. This implies that there is likely to be a range of slope angles which indicate instability.

The model sensitivity to the runoff parameter is perhaps greater as there are only three broad classes. The Standard Percentage Runoff (SPR) is an index derived by hydrologists to estimate river flows and is not directly comparable to overland flow. Although this index indicates those soils where runoff is likely, the SPR also includes a component of rapid response to rivers and streams by water flowing through the soils. This is especially true for alluvial soils and other soils found close to the river network, and so these soils may be in a higher erosion risk class than is

warranted. The soils developed on glacial lodgement till have an estimated SPR of 39.7%, which puts them very close to a runoff category boundary. Clearly these soils may actually generate more runoff at times, thereby enhancing the erosive force of the overland flow. The SPR is an averaged statistic based on measured runoff events. However, the temporal variability in moisture content, which greatly influences runoff, is not taken into account explicitly, and so the runoff response of the soil may vary throughout the year as moisture contents vary. Thus the dynamic component of the runoff term is lacking within the rule-base.

The combination of runoff and slope gave a ranking of the erosive power of any overland flow which is generated. However, as shown earlier, this ranking seemed to be slightly unstable and required an adjustment within the lower class of runoff in order to keep a degree of compatibility within classes. When the erosive power was crudely estimated by multiplying the amount of runoff by the slope angle, the relationship seemed to be non-linear. This necessitated a slight adjustment to the categories where slopes were steep (18-30°) but the predicted runoff was only 20%. The erosive power was thought to be more closely related to the preceding category and to those categories with less steep slopes but greater runoff.

The final parameter used in the model was the texture of the surface soil horizon. There is a considerable body of literature that could be used to devise a ranking of relative erodibilities for mineral topsoils but there was a lack of data pertaining to organic surface layers. What evidence there was on the behaviour of these layers was contradictory.

The evidence for the ranking of mineral soils came largely from recent studies to provide data on their detachability and cohesiveness for process-based erosion models. As these properties are not the same, and data for both properties were not available for all soil textures, there was a degree of subjectivity in the rankings used. However, as the mineral soils textures were grouped into three broad classes, some of the ranking error may have been reduced.

The rule-based model did not take into account the reduced aggregate stability of soils with < 3.5% organic matter content, nor the increased aggregate stability of soils with greater organic matter contents (for example, those described as humose where organic matter contents are > 10%). This was partly due to the scale of the map output and the difficulty of applying these additional rules consistently over all Soil Series. If the rule-base were to be applied at a finer resolution, these additional parameters could be incorporated in future, more detailed studies.

The soils with organic surface layers were essentially split into two groups: peats, including blanket and basin peat, and organo-mineral soils such as peaty gleys, peaty podzols, peaty rankers and humus-iron podzols. The organic surface layers of the peats were considered to be highly erodible under all conditions, while the remainder varied according to runoff and slope. The lack of documentary evidence on the relative susceptibility to erosion of these organic layers compared with mineral soils meant that the two groups had to be treated separately in the classification. This represents a major area of uncertainty in the rule-base.

11 MAP RELIABILITY

In essence only two map datasets were combined in this exercise: the slope map derived from a 1:50 000 DEM, and the 1:250 000 scale soil map from which the spatial distribution of surface textures and runoff classes were derived.

The digital elevation data were interpolated by the Ordnance Survey from contour lines (the details of the methods used are not known) and converted to a 50 m grid whereby each 50m by 50 m cell was allocated an elevation. There are some general principles pertaining to these types of data. Contours will be spaced widely in terrain with low relief, giving sparse data for interpolation and hence low relative accuracy in these areas. Conversely, areas with high relief will have many contours and hence more data for interpolation, with a consequent improvement in the accuracy. However, as the heterogeneity is also greater in these areas, the interpolation method assumes more importance. Although used within the GIS at the resolution of a 50 m grid, the underlying dataset is a 1: 50 000 scale map which determines the accuracy of the contours.

The 1:250 000 scale soil map was converted to a 100 m grid cell coverage (1 hectare). However, the underlying dataset has a minimum mapping unit of around 75 hectares (Soil Survey Staff, 1984). This leads to one of the major disadvantages of using the 1:250 000 scale soil map; that is, due to the spatial heterogeneity of soils in the landscape, the soil map units generally comprise more than one soil type. Thus a single soil type had to be chosen to represent each unit for the purposes of producing a map. In theory, the chosen soil type may only represent 35% the area covered by that map unit. About 25% of the map units classified had contrasting soil types, which meant that the final erosion class represents less than 100% of the area covered by that map unit. It was rare for the map unit to be represented by a soil type which covered less than 50% of the area but there were a few instances where 50% of the soils in a map unit were in one texture/runoff category and the remainder in another. In these cases, the most erodible soil combination was selected to represent the unit. This has led to large areas of land being classified as if they comprised only blanket peat and deemed to be highly erodible (for example, in the Western Seaboard.

As soil texture and runoff were derived from the same spatial dataset, it was possible to maintain the link between the two properties; that is, the runoff and texture classes were determined for each soil type within a soil map unit and the dominant pairing selected to represent that unit. If the datasets had been treated totally separately, then the soil which generated the most runoff would have been combined in overlay with the soil texture most susceptible to erosion, even if this combination would not occur in reality. This referential integrity was maintained throughout these two datasets, but unfortunately it could not be extended to include the slope coverage. There are known links between the soil types occurring within a map unit and slope (for example, Bibby et al., 1984). However, it was not possible, given the scale of the mapping and the resolution of the datasets, to use this information to refine the map output.

12 CONCLUSIONS AND RECOMMENDATIONS

This study aimed to produce a set of transparent decision rules to classify the soil erosion risk by overland flow and a set of maps showing the extent of this inherent geomorphological risk in Scotland. The necessity to produce this risk assessment for all of Scotland limited both the development and the implementation of the rules to only those datasets available at the national scale. However, it is hoped that, with some refinement, the rules could be applied at a finer resolution. The erosion risk has been treated as a static land quality, but future developments should incorporate more dynamic components, such as rainfall variability and timing of rainfall events, as well as the presence or absence of vegetation cover related to cropping cycles and land management.

A major problem with the use of the 1:250 000 scale soil maps is that the map units comprise more than one soil type. These soil types may well have contrasting erosion risks. The map output is only one realisation of the erosion risk as it can only show the dominant erosion class. However, the attributes related to each map unit and soil type are stored within a database which can be interrogated to assess the nature of the hidden erosion risk. More detailed maps could be produced from the information in this database which, for example, would show the proportion of map units that occur in the various erosion classes.

The use of the HOST property, Standard Percentage Runoff, to establish the likely runoff potential for a particular soil was not entirely successful as this parameter describes the rapid response hydrograph rather than overland flow. Future development of the rules should include methods to predict the permeability of the soil and its storage capacity, from which estimates of infiltration excess can be determined. In this respect, a move towards the use of a more physically-based simulation model applied to specific catchments may provide a more objective and physically realistic assessment of the likely erosion risk.

The study has highlighted the lack of objective data on the erodibility of Scottish soils and, in particular, has shown that there is a significant gap in our knowledge of the behaviour of organic surface layers. A recommendation must be that efforts should be made to assess the erodibility of both mineral and organic topsoils in Scotland by experimentation.

A vegetation cover provides protection for erosion by intercepting heavy rainfall, by disrupting overland flow and by sieving out entrained soil particles. Therefore, soils which are vegetated tend to be less easily eroded. The ranking of erosion susceptibility given in this study was done assuming no vegetation cover and represents the potential of the land to be eroded. The actual erosion susceptibility depends on the nature of the land cover. Certain management practices and land uses involve the land being periodically cleared of its vegetation cover. This can occur yearly, as in the case of arable agriculture, periodically, as in the case of improved grassland, or over several decades, as in the case of commercial forestry. Similarly, land under semi-natural vegetation (such as heather moorland) may be periodically burnt or become overgrazed and poached, which temporally reduces the vegetation cover. In all these cases, the soil is more likely to be eroded than if

there was a permanent vegetation cover. As vegetation can be more easily modified than the other attributes used to devise the rule-base, it is possible to use the model to examine the potential for increasing or decreasing the extent of erodible soils by varying land use. Throughout the implementation of the rules, it was assumed that the soil surface was devoid of a vegetation cover. A more realistic assessment of the potential erosion risk could be made by overlaying land cover data to identify those areas where there is likely to be a full and continuous vegetation cover.

Thus, although this study has produced a first attempt at assessing the inherent risk of soil erosion by overland flow for all of Scotland, in order to gain a better insight into the likelihood that erosion will occur, it will be necessary to take the land use and land management into account. It is recommended that the incorporation of land cover data into the risk assessment be made. This will allow areas at greatest risk to be identified and future experimentally based work targeted to these areas.

In summary, this work addressed a major gap in knowledge about the soil erosion risk throughout Scotland and will allow future work to be more focused. In particular, there are a number of recommendations that can be made in order to progress the understanding of soil erosion in Scotland and how this risk is managed. These are as follows.

- Land cover data should be overlain with the soil erosion risk assessment to derive maps of the actual risk of erosion.

- There is a significant lack of objective data on the erodibility of Scottish soils (both organic and mineral). Experimental procedures should be put in place in order to assess the relative erodibilities of all Scottish topsoils (both organic and mineral).

- There should be a move towards more process-based assessments of the soil erosion risk for detailed investigations. This will also allow an appraisal of the effects of the timing of rainfall events and the role of antecedent soil moisture conditions as well as the effects of soil hydrological properties and land management on the risk of soil erosion.

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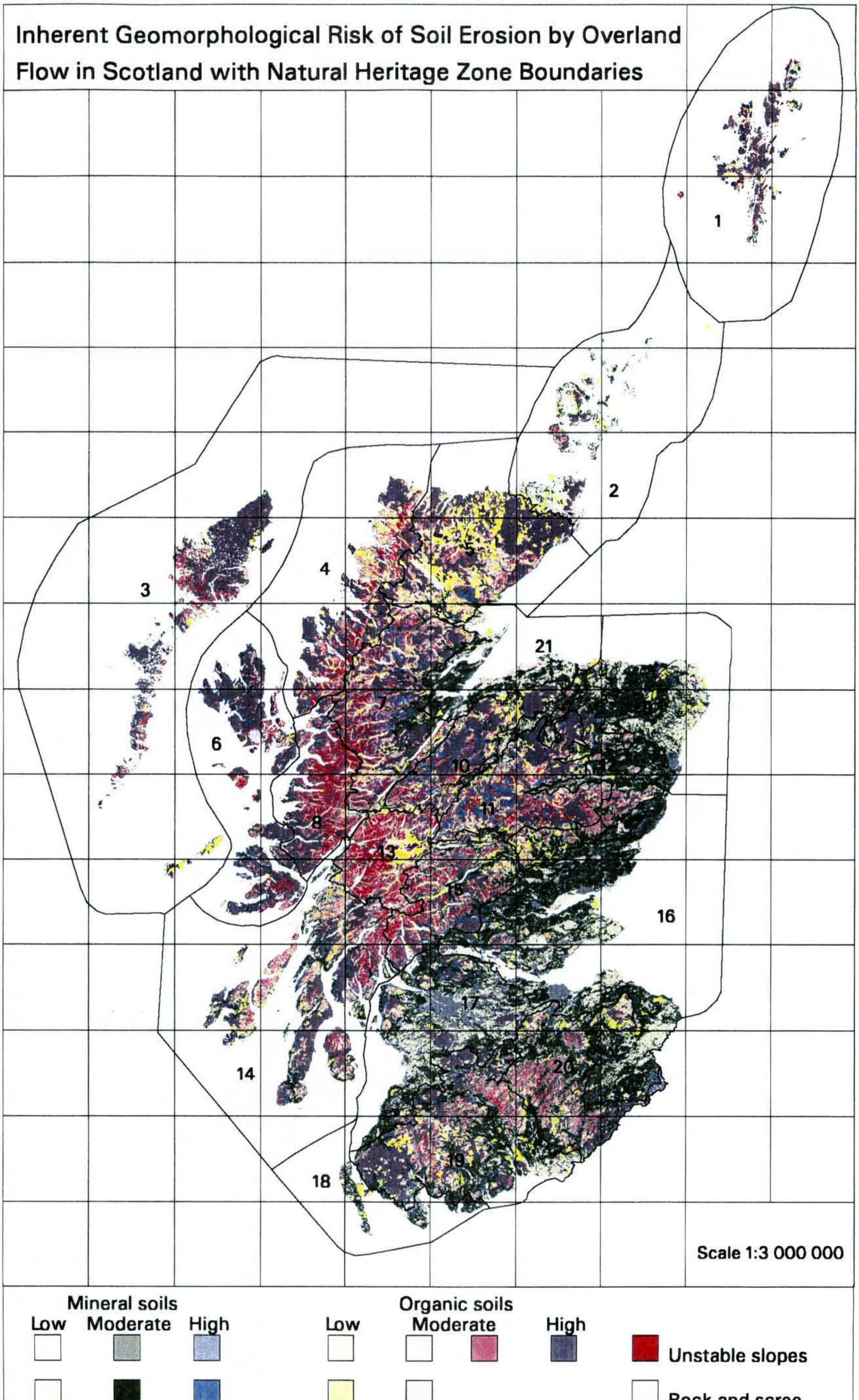
APPENDIX 1. Classification of slopes adapted from Young (1972)

Class	Degrees
Precipitous to vertical	45-90
Very steep	30-44.99
Steep	18-29.99
Moderately steep	10-17.99
Moderate	5-9.99
Gentle	2-4.99
Level to very gentle	0-1.99

After Young (1972)

APPENDIX 2. 1:3 000 000 scale map of the inherent geomorphological risk of soil erosion by overland flow in Scotland (Copyright: MLURI/SNH).



Inherent Geomorphological Risk of Soil Erosion by Overland Flow in Scotland with Natural Heritage Zone Boundaries

SCOTTISH NATURAL HERITAGE

Scottish Natural Heritage is an independent body established by Parliament in 1992, responsible to the Secretary of State for Scotland.

Our task is to secure the conservation and enhancement of Scotland's unique and precious natural heritage - the wildlife, the habitats, the landscapes and the seascapes - which has evolved through the long partnership between people and nature.

We advise on policies and promote projects that aim to improve the natural heritage and support its sustainable use.

Our aim is to help people to enjoy Scotland's natural heritage responsibly, understand it more fully and use it wisely so that it can be sustained for future generations.