Geological Survey Ireland

National Landslide Susceptibility Mapping Project Summary

Geological Survey Ireland is a division of the Department of Communications, Climate Action & Environment.

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Prepared By	Date	Comment
Charise McKeon	03/11/2016	

Reviewed By	Date	Comment

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1 Introduction

Following two major landslide incidences in Ireland in 2003 in Galway and Mayo the Geological Survey Ireland established the **Irish Landslides Working Group (ILWG)** in 2004. It was felt important that it should be a multi-disciplinary team, bringing together various types of expertise which are relevant to landslide studies. This point is often stressed in the international literature on the subject (Brunsden, 1993). The Group includes expertise on geology (Bedrock and Quaternary), geomorphology, geotechnical engineering, planning, and GIS. The participants were drawn from state and semi-state agencies, and also the universities. The main objectives of the ILWG were;

1. Build a national database of past landslide events
2. Examine geotechnical parameters with regard to landslides.
3. Assess the potential for landslide susceptibility mapping in Ireland.
4. Make recommendations on the integration of landslide hazard issues into the planning process.
5. Promotion of landslide research in Ireland.
6. Raise public awareness about landslide hazard in Ireland.

This report provides an overview of the Landslide Susceptibility Project being undertaken by the Geological Survey, and can be read as a lay user guide to the output Susceptibility maps. There are two main strands to the study: the extension of the landslide inventory and the development of national landslide susceptibility mapping.

When the project commenced there were less than 200 recorded landslides in the GSI inventory database. This represented statistically too small a number of incidents on which to develop a robust relationship between the incidence of landslides and the associated geographical factors pertinent to the occurrence of these events. Thus the extension of the landslide inventory has been an essential component in the development of the methodology to create national susceptibility mapping.

The selection of a methodology to create susceptibility mapping commenced with an extensive literature review of approaches taken in a variety of projects from many different countries. This confirmed that there was no single universal method but that the key issue was an approach that suited the available datasets and the project objectives. Readers seeking the projects technical and methodology reports can find these listed in Appendix C.

Although some statistical approaches were also explored, the literature research and the requirement for a methodology that could be applied to Ireland as a whole coupled with the uncertainty as to how many additional landslides would be found by extending the inventory lead to a methodology known as the Unique Condition Unit (UCU) approach.

As the name suggests, UCUs are parcels of terrain where a set of attributes are combined in a unique way. In the context of landslide susceptibility mapping the attributes being considered are slope, soil type and an index which is a measure of overland flow concentration from intense rainfall events. The latter parameter has been called the Topographic Flow Index (TFI).

The various elements in the development of the project are discussed in more detail below, however **Section 5 Landslide Susceptibility Mapping** can be read as a stand-alone section, if desired, and relates to the production of susceptibility map as illustrated in **Appendix A, Figure A1**

(Note: All large figures and tables have been placed in Appendices A and B, but minor illustrations are in the body of the text.)

2 Literature Review

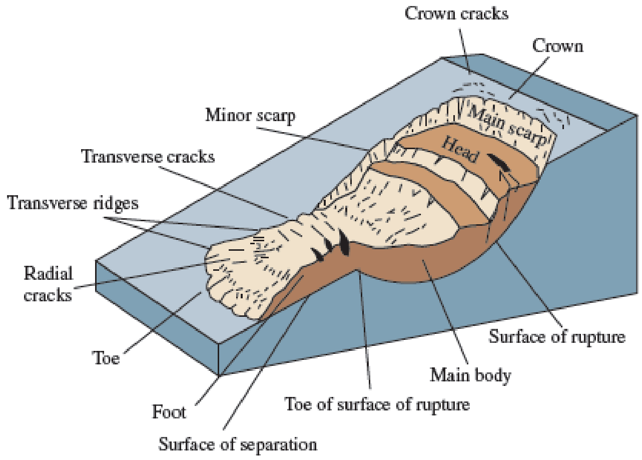
A comprehensive literature review was undertaken at the beginning of the project to review methodologies that had been used in landslide studies around the world and from which, the appropriate approach for this project was determined. It transpired that many of the papers related to project specific studies (e.g. roads, pipelines, development) and only a few to large regional assessments.

Statistical approaches which relate various characteristics of the landscape and physical geography with the incidence of landslides are a popular approach, but require a large inventory of landslides to formulate the statistical relationships. Given the initially small inventory within the study area and uncertainty as to how many additional events would be uncovered an alternative approach known as Unique Condition Units (UCU) was recommended as the most pragmatic approach. Although methodologies have become more computational in the past decade with developments in processing power and software, expert judgement still has an important role and this can be readily incorporated into the UCU approach.

It transpired that in the course of the project sufficient landslides were identified to enable a statistical approach and two methods were evaluated. Both of these 'worked' in the sense that they could produce landslide susceptibility mapping, but the mathematics is more convoluted than that used in the UCU approach which appears to produce equally valid results. Thus, it was decided to retain the UCU approach as it is more transparent and more likely to be acceptable to the general public.

3 Inventory Development

Various sources (BGS & USGS) show diagrams of 'idealised' landslides in which many parts of the landslide are named. This particular diagram (USGS) which shows a rotational type failure may be a useful concept when a recent landslide is being examined, but even then not all of the named features may be present and the cross section showing the slip surface is not visible in reality. In old landslides the 'sharp' features shown in diagrams rapidly erode and with weathering and re-vegetation the distinctions become blurred. Often the only obvious visible feature remaining will be the scarp / head region (somewhat rounded) and a dished hollow. Thus the process of identifying and classifying old landslides can be difficult and carries a degree of uncertainty.



The inventory development consisted of several activities: identification of 'new' landslides, rationalisation of the GSI database, validation including fieldwork and documenting the location and attributes of the newly identified landslides.

3.1 Aerial Photo Interpretation

The landslide inventory development commenced with examining aerial photographs for candidate landslides. Aerial imagery datasets consisted of three sets of high resolution ortho-photographs. Images were taken in 2000, 2005 and 2010, respectively and were regarded as complementary to each other since the direction of sunshine (hence also the shadow) varies between both sets. The temporal aspect of the landslide occurrences was also clearly evident when comparing the two datasets. To ensure precision, especially in shaded areas, Google Earth imagery was interpreted concurrently with the aerial image datasets, since its 3D feature provided extra clarity. An important aspect of this work was the 'randomisation' of work packages to ensure observers were kept 'fresh' by being presented with different types of terrain. Also there were various systems of cross checking, recording and quality control built into the process.

3.2 Candidate Landslide Validation

Once candidate landslide locations had been identified on the aerial photographs, independent validation was undertaken by an experienced geomorphologist. Given the large number of candidate landslides it was not feasible, either in terms of time or budget, to physically examine all locations in the field. Thus, the pragmatic approach to validation was to use a 3D visualisation system within GSI and if uncertainty remained then schedule those locations for fieldwork.

Generally each fieldtrip was for one week and undertaken as a two person team due to the often remote locations. A total of 8 pre-defined areas were targeted covering areas which ranged from county level to smaller 20-30 km^2 sites. Preparation consisted of identifying areas, access and candidate locations that could be tackled within the timescale, plus some fall back options to cater for the possibility of severe weather limiting access to particularly remote areas or higher elevations. Customised base-mapping was prepared as it offered significant advantages over standard OS mapping. The use of aerial photography background at a scale of 1:10,000 to 1:15,000 aided feature identification and superimposed on this were the landslide locations and other topographic details. An example of the type of base-mapping produced is shown in **Figure A2.** A handheld GPS was used to navigate to specific locations and generally indicated a precision of ±10m. On a number of occasions fresh landslides that post-dated the 2005 or 2009 aerial photographs were identified during fieldwork. Field notes and photographs were taken at the landslide sites.

Clearly there is little difficulty in confirming recent landslides, but with older historical landslides a somewhat forensic approach is required. Identification of landslides starts from an understanding of geomorphological processes and factors that may trigger an event. With old landslides the distinguishing features depicted in the classification diagrams have generally been eroded and smoothed and the whole area re-vegetated. Similar features can arise from processes other than landslides, thus the presence of possible triggering mechanisms in the surrounding topography needs to be considered. In essence, the objective is to establish whether there are a sufficient number of landslide type characteristics and causative factors without contra-indications to justify classifying the feature as a landslide. Some examples of recent and old landslides ranging from small to large events are shown in **Appendix B, Figure B1** to **B7.**

3.3 Documentation (post fieldwork tasks)

An objective of the landslide susceptibility study is to classify and delineate the extent of the newly identified landslides. Landslides may be shown as points located at the head scarp or as polygons depicting the perimeter of the disturbed area. Associated with each landslide is data relating to land use, local vegetation, soils type, geology etc. and other meta-data such as the shape and visual clarity of the feature. This information is recorded as it will be of assistance if any follow up study into particular types or subsets of landslides is undertaken. The purpose and nature of data such as land use and soil types is self-evident, however the 'Visibility' and 'Shape' characteristics require some explanation.

3.3.1 Visibility

In this project, a high proportion of the older landslides are often indistinct and irregular in shape. Although a point location at the head of the landslide can be indicated, the task of digitising the perimeter may be more subjective. Furthermore, once a point or polygon is entered into the GIS database the only way of knowing the level of subjectivity is by recording associated meta-data.

Given these practical difficulties, the approach has been to derive a two criteria classification system to apply when the perimeters are digitised. The first factor is how well the landslide stands out from the surrounding landscape and is assigned to a three level scale (A, B, C). The second is the completeness of the boundary around the disturbed area and whether all three elements, scarp, sides and run-out can be identified. This is also assigned to a three level scale (1, 2, 3). The resulting alpha-numeric code is recorded and provides a form of quality assurance flag.

3.3.2 Shape

Although there are classification schemes for landslide type e.g. (BGS / Varnes, 1978), no 'plan' shape classification system has been identified in the literature therefore a project specific scheme has been devised.

The shape classification scheme is based on a three level hierarchy with each level providing a finer level of detail - where this is applicable.

In outline the three levels are:

- General shape: *Elongated, Ellipse, Teardrop, Irregular*
- Variations: *Straight / Curved, Irregular, Inverted, Multiple (group)*
- Scarp & Toe: *Multi-scarp (n, m), Multi-lobe (n, m)*

The latter attributes have two values that indicate the number of scarps / outrun lobes and their length in proportion to the landslide as a whole. This is useful in describing landslides which may have merged at the toe or diverged from a common scarp area. The proximity and geometry of these scarps and lobes is also relevant to deciding if a feature is a single landslide or multiple events and so can affect the inventory count.

3.3.3 Miscellaneous Attributes

In addition to the above visibility / shape description fields a wide range of other attributes relating to the landslide are recorded. Some of these are associated with the geometry and include, for example length, width and area. There are also a number of fields holding information on the local soil type, vegetation cover, land use, topography (elevation / landform) etc. In addition there is meta-data relating to who / how the landslide was identified and verified.

An example of how the visibility, shape and some of the miscellaneous attributes are used is given in **Figure 1** below. These attributes allow the rapid and systematic selection of sub-sets of landslides that may be of particular interest for subsidiary studies.

The image shows two peatslide areas. The right hand area was initially considered to be a single slide with two head scarps, but given the separation is now interpreted as two landslides coded as:
Visibility: *B2* ***Shape****: Elongated, Irregular, Merged*
Areas: *15,705m^2 and 10,080m^2* ***Aspect Ratios:*** *9 and 7*

The left hand area has been interpreted as a single peatslide and coded as:
Visibility: *B2* ***Shape:*** *Irregular*
Area: *39,945m^2* ***Aspect Ratio:*** *3*

Figure 1 Illustration of Landslide visibility and shape

3.4 GSI Landslide Database

As part of the initial work of the Irish Landslides Working Group a comprehensive database of landslide events in Ireland was compiled. Landslide events, the earliest records of which date back to 1488, were added from a variety of sources. This dataset was fundamental to the work carried out on landslide mapping in particular to the Landslide Susceptibility Map. Results from the various field campaigns (figure 2) now form part of this database. The National Landslides Database has recently been restructured and incorporated into a Geodatabase as part of the development of the GSI's dedicated Landslide Viewer and as part of a recommendation from the Irish Landslide susceptibility Mapping Project. The database now holds some 2700 events.

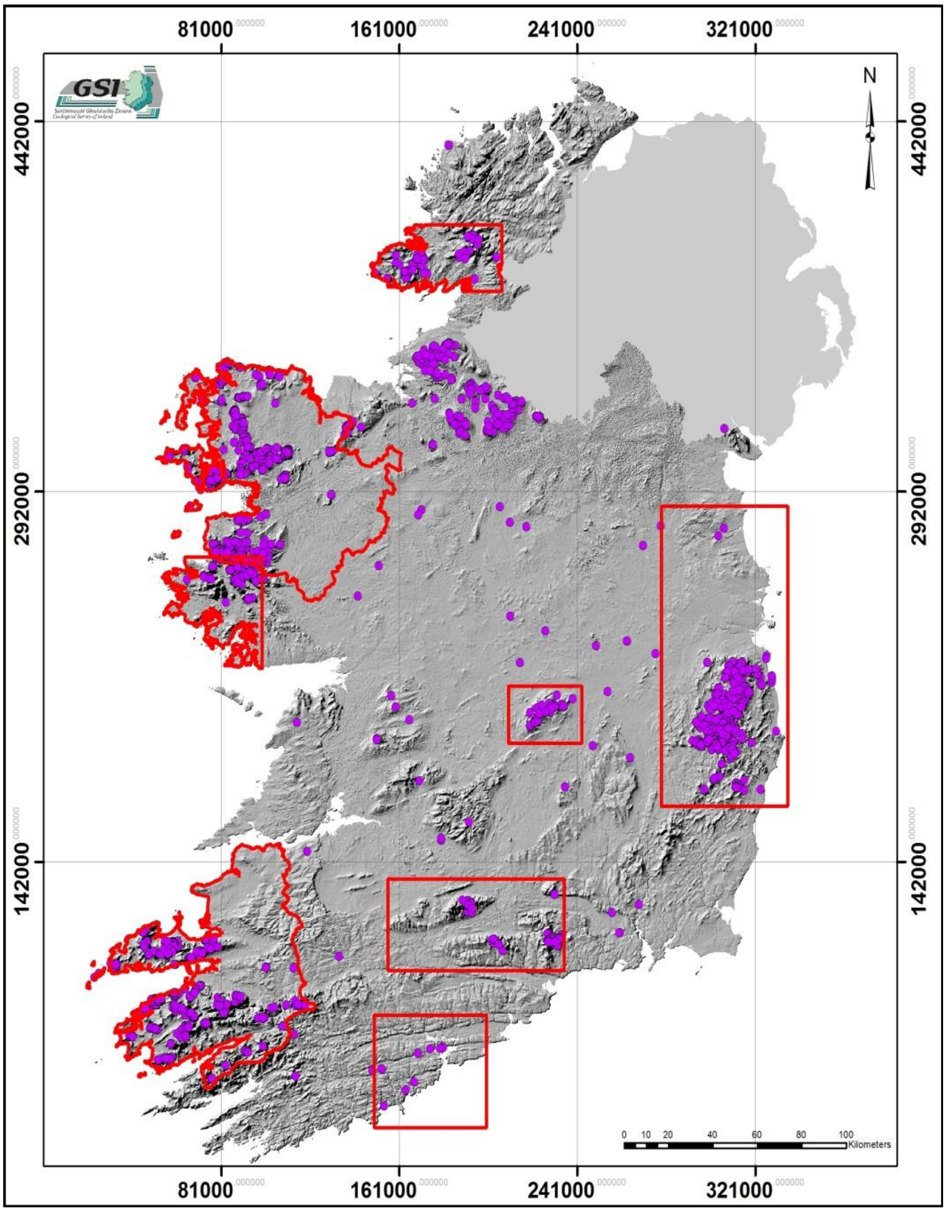


Figure 2: Areas of landslide inventory mapping 2011 - 2013

4 Unique Condition Units

In the context of landslide susceptibility mapping the attributes being considered are slope, soil type and a Topographic Flow Index (TFI). At any particular location these combine to give what is termed a Unique Condition Unit (UCU).

The attraction of the UCU methodology is the simplicity of the concept – if a landslide has been observed in an area with a particular combination of attributes, then the rationale is that if this combination occurs elsewhere that location is also susceptible to landslides. Furthermore, different numbers of landslides will have occurred in these UCU's hence there is a way to rank them in terms of their susceptibility to landslides.

4.1 UCU Variables

The UCU concept is perhaps deceptively simple because the maps of slope, soil, and TFI are very different in character and yet they have to be combined in some way to perform the analysis. The number of combinations must be kept to a manageable set commensurate with the available landslide inventory data.

Soil types are by their nature already categorised, however there are too many for UCU purposes and therefore these require grouping. In addition, the slopes and TFI maps are continuous variables which must be reclassified into discrete ranges. A variety of options for categorisation of the variables have been studied (see reports in Appendix C for details) and in summary the final configurations are as described below.

4.1.1 Slope Categories

The slope is derived from OSI 20m digital elevation data and values can range from 0 degrees (horizontal) to 90 degrees (vertical). Several approaches were considered for subdividing this range and the consensus was that smaller intervals should be applied at the lower angles as this improves the sensitivity of the method. The nine intervals used in the method are shown in **Table 1** below and **Figure A3** is an illustration of slope mapping. Eight intervals were used in the UCU model as no landslides currently mapped were found to occur in slopes > 65 degrees.

Table 1: Slope bands with band intervals and associated land areas

Slope (Deg)	**0-3**	**3-6**	**6-10**	**10-15**	**15-20**	**20-30**	**30-45**	**45-65**	**65-90**
Interval	3	3	4	5	5	10	15	20	25

4.1.2 Soil Groups

Soil classification is a more complex and subjective task than the slope classification. For this project the Geological Survey's national quaternary geology map was used. This contains 69 sub-soil types as well as additional areas such as water bodies, urban areas and land use areas. This level of detail is unnecessary and also intractable within the UCU approach.

Several options for aggregation of soil types have been considered. The final arrangement, based on grain size and likely geotechnical characteristics, gives 7 groupings of which two (Water and Made Ground) are not actually soils, but need to be included to avoid gaps in the mapping. The spatial distribution of these materials is best illustrated pictorially as shown in **Figure A4** and is supported by a description of these groupings and associated abbreviations in **Table A1** that follows the figure.

4.1.3 Topographic Flow Index

It is recognised that extreme rainfall events often trigger landslides, thus it is desirable to consider a measure of rainfall runoff flux. Many studies have been undertaken into the process of overland flow arising from rainfall events. These studies generally fall into three categories: (1) catchment modelling / flooding, (2) habitat development and (3) sediment transport. The actual modelling of these events is dependent upon the discipline and topic of interest.

The digital elevation model can be processed to derive a measure of how overland flow is concentrated or dispersed by the terrain and also to take account of flow velocity. The algorithm produces small values at watersheds and large values where the overland flow spills into streams. The watercourses themselves have very large flow index values, but for the purpose of landslide studies the watercourses are ignored. The land based range of numbers has been divided into three categories: Low, Medium and High TFI and **Figure A5** is an illustration of mapping for this index.

4.2 Combining Parameters

Given these groupings it is evident that there could be 8 slopes x 7 soils x 3 TFI or 168 potential UCU combinations. However, in practice it will be found that not all combinations occur across Ireland as a whole. The illustration in **Figure A6** shows the complex pattern of UCU's that arise when these three parameters are combined. In addition to this graphical presentation it is also possible to summate the areas of these UCU's and tabulate the areas by slope / soil / TFI.

5 Landslide Susceptibility Mapping

The concept of combining geographical attributes of the landscape to create Unique Condition Units (UCU) has been described but taken alone they do not provide any indication of the susceptibility of landslides. However, the number of landslides falling into each of the UCU's can be determined and when divided by the area of the relevant UCU this gives a landslide density value (landslides / km^2) which is a measure of susceptibility.

The end product of this process is a national landslide susceptibility map as illustrated in **Appendix A, Figure A1.** It is intended that this map be used at a scale of 1:50,000 and may contain other information layers such as country borders, habitation etc. and contain selectable layers on any on-line versions.

5.1 Landslide Inventory

The inventory of landslides (as of May 2016) is shown in **Table A2** which is a count of the numbers of landslides within each UCU. The main trend that can be observed in the data, when considering all landslides together, is that the numbers initially rise with increasing slope then decline, with the exception of those recorded in rock near surface at higher slope ranges. The initial rising trend is unsurprising and the explanation for the subsequent decline is that there is less terrain at the steeper slopes hence fewer observations, even although the tendency for landslides may be higher on steeper ground.

5.2 Landslide Density

To create susceptibility mapping the inventory is 'normalised' and expressed as a density of landslides per km^2. This is done by dividing the inventory count by the areas of the relevant UCU to give values for each of the UCU's represented in the study area. The land areas of each UCU are shown in **Table A3.**

The values in **Table A2** and **Table A3** can now be processed to create the incidence of landslides in each UCU for which data is available. These values are shown in **Table A4** Note that to make the numbers more manageable they have all been scaled up to express density as landslides / 100 km^2.

It will be observed in these tables that some UCU's have no landslides. In part this is because particular UCU's are absent as, for example, peat would not develop on steep slopes. Those combinations not found within the study area are greyed out.

In addition, null observations may occur for two other reasons; (a) there were genuinely no landslides or; (b) observational difficulties meant that old landslides were not detected. Condition (a) is most likely within the low slope areas of the table but (b) could be applicable within any UCU, although most likely in two specific sets of circumstances.

Observational difficulties with aerial photography occur within narrow incised valleys which are heavily vegetated with woodland and scrub making it difficult to detect candidate landslide locations. This happens to frequently coincide with soil type FMR which occurs in these locations.

The other type of terrain in which there are observational difficulties is steep, particularly north facing, slopes which are often in shadow, thereby masking the visible signs of candidate landslide locations.

5.2.1 Extrapolation

In order to create a comprehensive landslide susceptibility map, all Unique Condition Units require a density value or susceptibility category. For those cases where there is no landslide inventory the gaps need to be populated with estimated values. This extrapolation can be thought of as in-filling in three different circumstances:

1. lower slope ranges - generally less than 10 degrees
2. upper slope ranges - generally greater than 45 degrees
3. isolated gaps between populated ranges

Not all gaps in the landslide density or susceptibility matrices are of equal significance when it comes to producing a susceptibility map and there may also be different degrees of confidence in the extrapolation process in different parts of the matrix. In the fullness of time as more landslides are added to the inventory, it is possible that any remaining gaps may be resolved, but in the meantime, procedures for extrapolation are required.

The lower slope ranges (1) cover large areas of Ireland (the average slope is around 3 degrees). We can say with confidence that in most cases the incidence of landslides should be virtually nil for slopes approaching zero slope and even for a few degrees of slope for medium to coarse granular material. These are defensible limits that can be applied.

In the upper slope ranges (2) it is also possible to provide a logical rationale for extrapolation. Generally steeper slopes become increasingly susceptible to landslides, with the possible exception of intact rock masses. Thus an upper bound can be set and the expectation is that this will be in the highest susceptibility category.

Furthermore, as the landslide density values are ultimately transformed into a limited number of susceptibility bands then provided any extrapolation method puts the appropriate UCU's into the 'Low' to 'High' susceptibility ranges then the mapping objective will be satisfied.

In theory the infilling of nulls in the inventory can be undertaken in two ways: (a) an arithmetical extrapolation using the table of landslide density values or (b) through inspection and judgement when landslide density values have been assigned to susceptibility bands.

Had there been a requirement to produce a continuous colour ramp map of landslide susceptibility then a fully populated table of landslide density values would be required. However, the objective is to create categorised mapping with a limited number of discrete susceptibility bands therefore option (b) has been used.

The derivation of the landslide susceptibility bands themselves is described in **Section 5** below, however once those have been defined then infilling for null UCU's is relatively simple. This can be done by inspection of the susceptibility bands where for the vast majority of cases it becomes obvious what values should be assigned to any gaps to ensure continuity and gradation across the table. The results of this approach are in **Table A5** where the distinction between data derived and interpolated susceptibilities categories are shown. Subsequently, this distinction can be maintained in the susceptibility mapping and it will be transparent as to which zones are based on inventory data and which are inferred. The area currently inferred within the national coverage totals approximately 4112 sq. km. (or 4.8%)

5.3 Specifying Susceptibility Bands

UCU's can be ranked from the least to the highest density of landslides with mapping rendered in two formats. The first uses the continuous numeric landslide density scale to produce a thematic map suitably coloured from low to high susceptibility. The second approach is to divide the numeric scale into a small number of bands with appropriate narrative to describe the susceptibility and attributes of each band. Following discussions with planning authority stakeholders it is this latter approach that has been taken forward

A key objective for setting the banding is to use a transparent method and to partition the range of scores into a limited number such as three, four or five bands. The break points between these bands are based on simple arithmetic or geometric progression, where the intervals are equal, doubling or trebling of the band size.

A series of tests has been conducted to examine the mapping output produced by various combinations of the number of subdivisions and band scales. It has been found that four bands with a scale multiplier of 2 (doubling) produces satisfactory thematic maps. In effect this specifies that the number of landslides falling into each band is in the proportions 1:2:4:8 which is a simple geometric series with a multiplier of two. In **Table 2** below, these proportions are shown as percentages and the inventory of landslides (2545) has been partitioned into these percentages as 'Target' numbers for each band A to D.

Table 2: A four band susceptibility scale with associated numbers and areas

BAND	STEP (4:2) %	Target Nos (2545)	Actual Nos	Area (km2)	Area %
A	53.3	1356.49	1609	2451.69	3.60
B	26.7	679.52	497	4704.11	6.90
C	13.3	338.49	292	5128.26	7.52
D	6.7	170.52	156	55873.37	81.98

The final step in creating the susceptibility banding is to assign the landslide incidence (density) values to bands A to D in proportion to the above table. The result of this is shown in **Table A5.** As it is not possible to subdivide UCU's the actual numbers differ somewhat when the UCU's are assigned to a particular band. The land areas within each band arise from a summation of the individual UCU areas contribution to each band.

5.3.1 Defining Susceptibility Bands

The number of bands and band interval is a numerical specification, but for these bands to be meaningful requires a set of descriptions that convey the likelihood at each level. The attributes under which the landslide susceptibility bands are described is shown in **Table 3** below.

Table 3: Attributes used in the description of Susceptibility Bands

Column	Description
Description	This is the 'susceptibility tag', defining a level of susceptibility and is elaborated upon in other columns which provide information on the physical geography, landslide incidence etc.
Physical Geography	This provides a description of the soil types and slopes which are the most dominant characteristics of a particular band. This has been done by abstracting information on the areas of soil types and slope bands.
Landslide Incidence	The banding itself expresses landslide susceptibility, but this provides some additional details of the conditions (in terms of slope and soil) particular to that band in which most of these slides have occurred.
Indicative Extent (by Number)	This indicates the expected percentage of landslides falling within each band although actual numbers will fluctuate slightly as the inventory develops and is updated.
Indicative Extent (by Area)	This is the land area encompassed within each band. It is a feature of the study area, but if the physical characteristics are generally typically of Ireland as a whole then the figures will be relatively stable.

These headings provide a structure in which the detailed descriptions for each band are formulated and this is shown in **Table A6**. It is anticipated that this table would be a necessary part of the map legend, or readily referenced for any on-line version of the mapping to provide a context for the mapping.

5.4 Validation

A number of sense checks have been undertaken on the susceptibility mapping output, both at regional levels and at a national level. In part these are visual checks on the spatial distribution of 'Low' / 'High' susceptibility areas to ensure that they conform to what expert opinion would expect. This includes, for example particular attention to peat on steeper slopes where it is recognised historically that these areas have a high susceptibility to peatslides.

In addition, the influence of particular variables has been checked through the production of mapping with the selective removal of a variable and examination of the changes. **Figure A7** shows an example of where changes would occur to the susceptibility banding if the Topographic Flow Index was excluded.

Another technique, known as Success Rate Curves, has been run on individual variables, pair-wise combinations, as well as all three UCU variables combined, to give a measure of the proportion of mapping explained by the variable. These checks show that the mapping is plausible and stable.

Upon completion of the national map validation was carried out on 15% of all landslides in the National Landslide Database, using geostatistical analysis for the division between the remaining 85% and the 15% being used for validation. The results showed that 92% of the validation landslides were located within areas categorised as High, Moderately High or Moderately Low susceptibility.

6 Conclusions

In undertaking the Landslide Susceptibility Project a wide range of issues have been explored and there are a series of reports dealing with specific topics in detail (See Appendix C). The purpose of this report is to summarise that work and describe the methodology that has evolved.

It is intended that the final susceptibility map can be understood and used without an understanding of the details of the methodology; however some of the intermediate steps may be of interest. Similarly, the approach to the inventory development and fieldwork may also be informative. With this in mind, and given that much of the output from the detailed studies is graphical, the appendices have been structured to provide a series of illustrations with brief annotations.

The literature study confirms that there are many approaches to landslide susceptibility mapping and some of the statistical approaches have been evaluated in this project. Some of these approaches are mathematically complex and some use a great many variables. The Unique Condition Unit approach as implemented in this project uses relatively few variables and is mathematically simple. However it has been evaluated and demonstrated to produce susceptibility mapping that appears as valid as any of the statistical approaches that were tested. An advantage of the UCU approach is that it is flexible enough to allow input based on professional judgement as used for the incorporation of the coastal strip influence (not currently incorporated).

The approach taken to categorisation of landslide susceptibility is through a four band scale ranging from 'Low' to 'High'. This uses the relatively simple concept of doubling the number of landslides within each band, such that the upper band has just over half of all known events. The lower band has a few landslides, not none, as to discount the possibility of isolated landslides in any circumstances may be unwise. Isolated landslides may occur due to anthropogenic factors which cannot be taken into account in the model. It is anticipated that this scale will satisfy the planning objective of requiring varying degrees of site specific controls or investigation.

A number of sense checks have been undertaken on the susceptibility mapping output. In part these are visual checks using professional judgement and in part on recognised mathematical procedures. These checks show that the mapping is plausible and stable.

Appendix A

The following appendix provides an example of landslide susceptibility mapping and a series of figures and tables that illustrate the underlying datasets used in this project.

The mapping does not scale as it has been reduced from A3 to fit the report format.

The allocation of susceptibility to the Unique Condition Units (UCU) is based mainly on inventory data (landslide events shown below) and in part from interpolation in areas where data is absent.

In order to make a distinction on the map between data derived and inferred susceptibility two schemes have been used and this is shown in the legend.

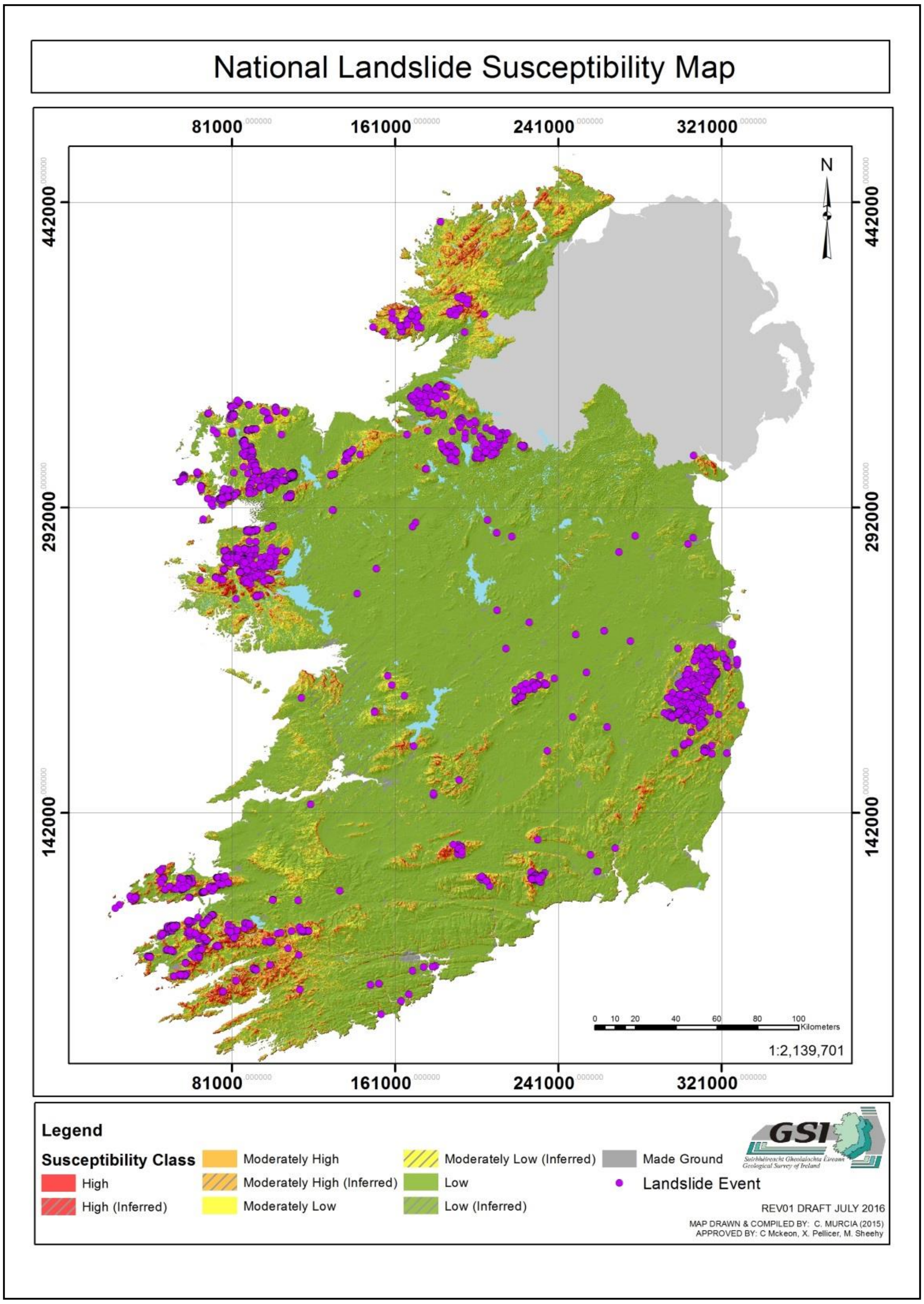
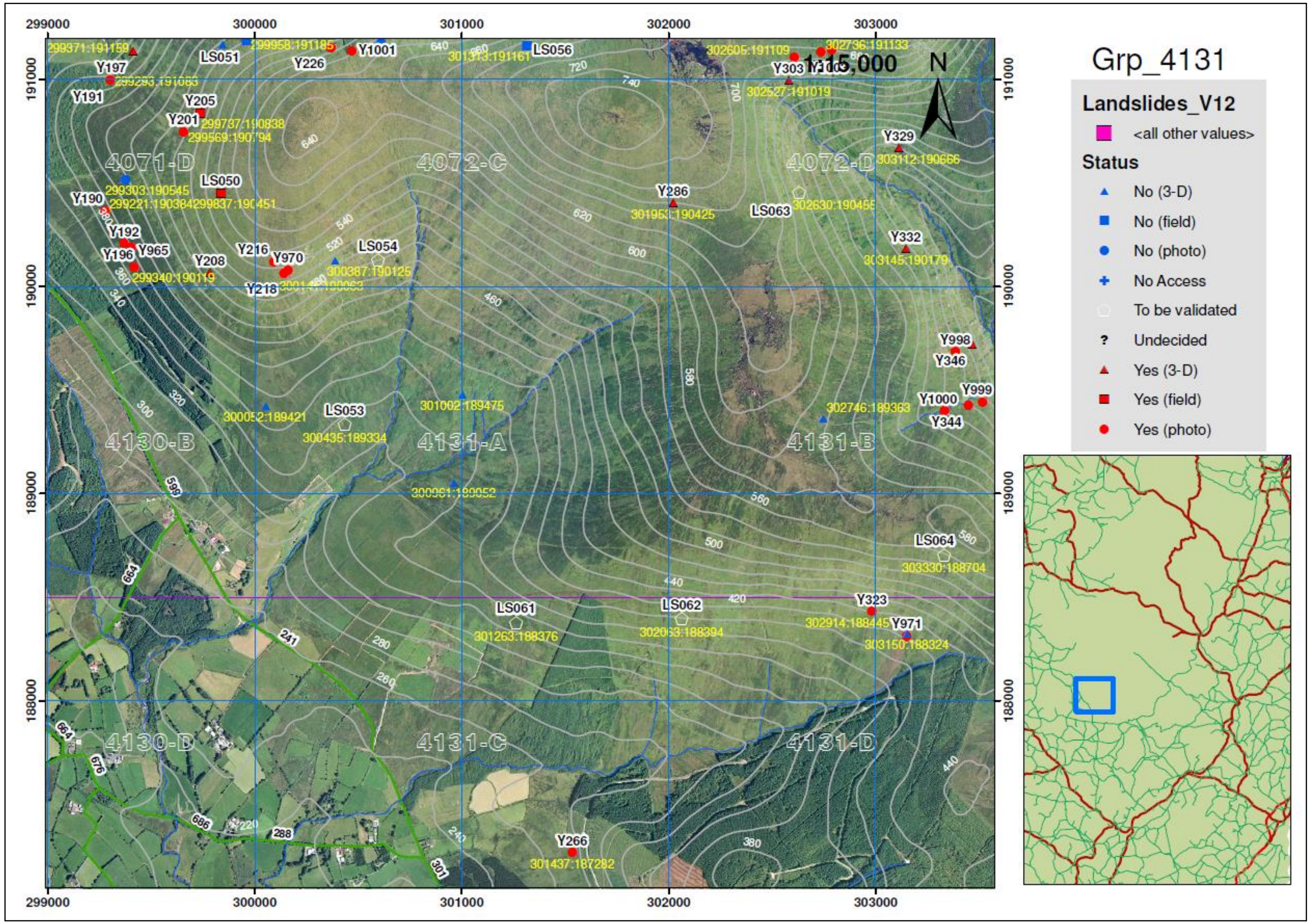


Figure A1: Illustration of a Landslide Susceptibility Map

Figure A2: Example of a customised base-map for fieldwork



This field map has been produced at a scale of 1:15,000 (when plotted on A3 paper) and the aerial photography shows more detail than an equivalent OSi map at the same scale.

The basic aerial photography has been enhanced by over-laying contours, water courses and the road network. In addition the symbology shows the current status of various landslide locations. A key map shows the detailed location in the wider context.

Having the aerial photography in the field assists with navigation around / through obstacles such as forestry and also shows minor tracks not shown on conventional mapping. In addition it is also convenient to have the image of what the aerial photography interpreter was seeing when a point was considered to be a candidate location

The national slope map was produced using a 20m DEM. As indicated in the legend the colours are graded from green to red (low to high slope categories). The slope was divided into eight classes for the purpose of the UCU model.
Landslide events are shown as purple dots. These are generally, but not exclusively, on steeper slopes as may be expected.

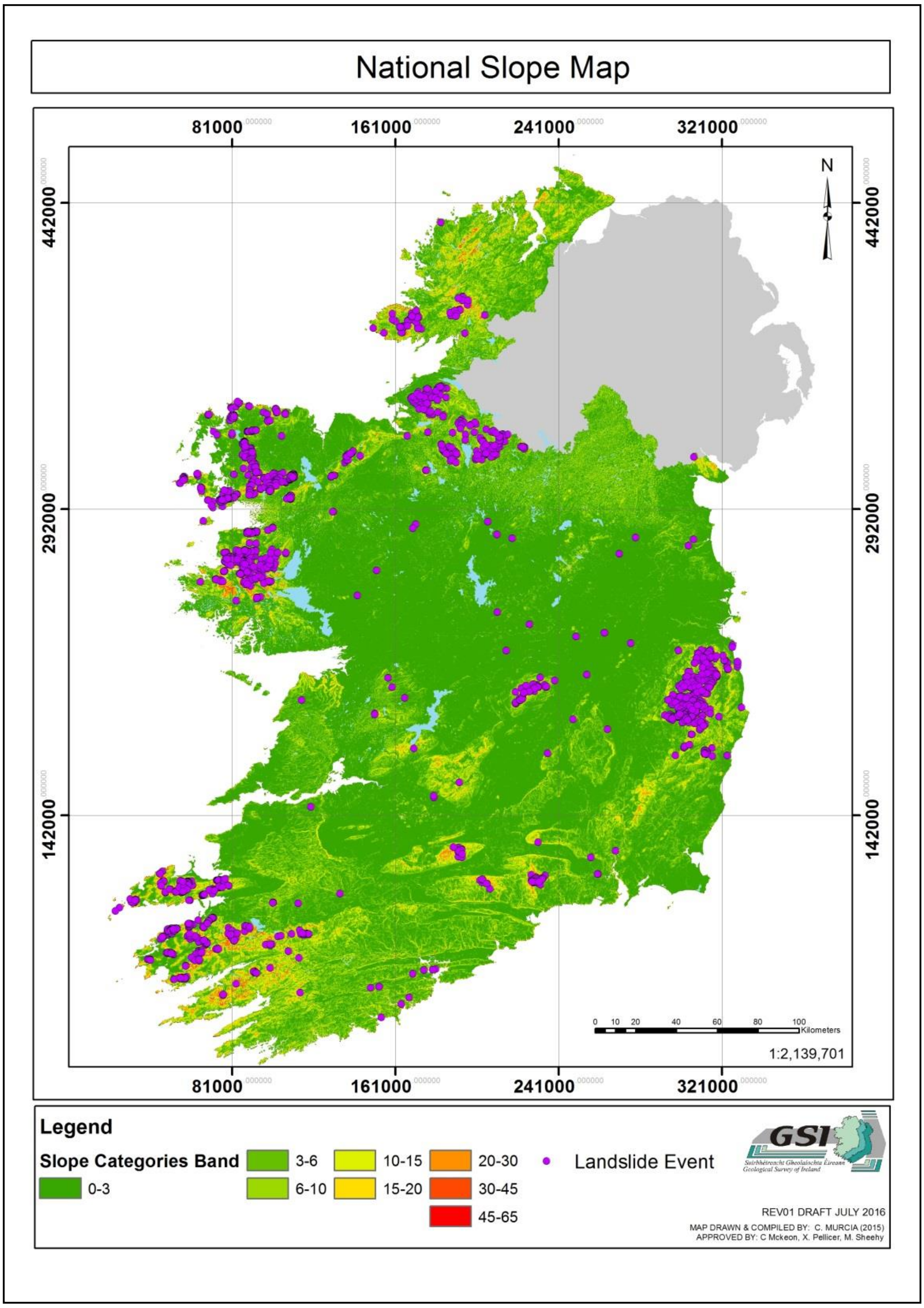


Figure A3: UCU Slope category map

A simplified version of the national quaternary geology map was produced based on grain size and likely geotechnical characteristics. 7 groupings of which two (Water and Made Ground) are not actually soils, but need to be included to avoid gaps in the mapping.

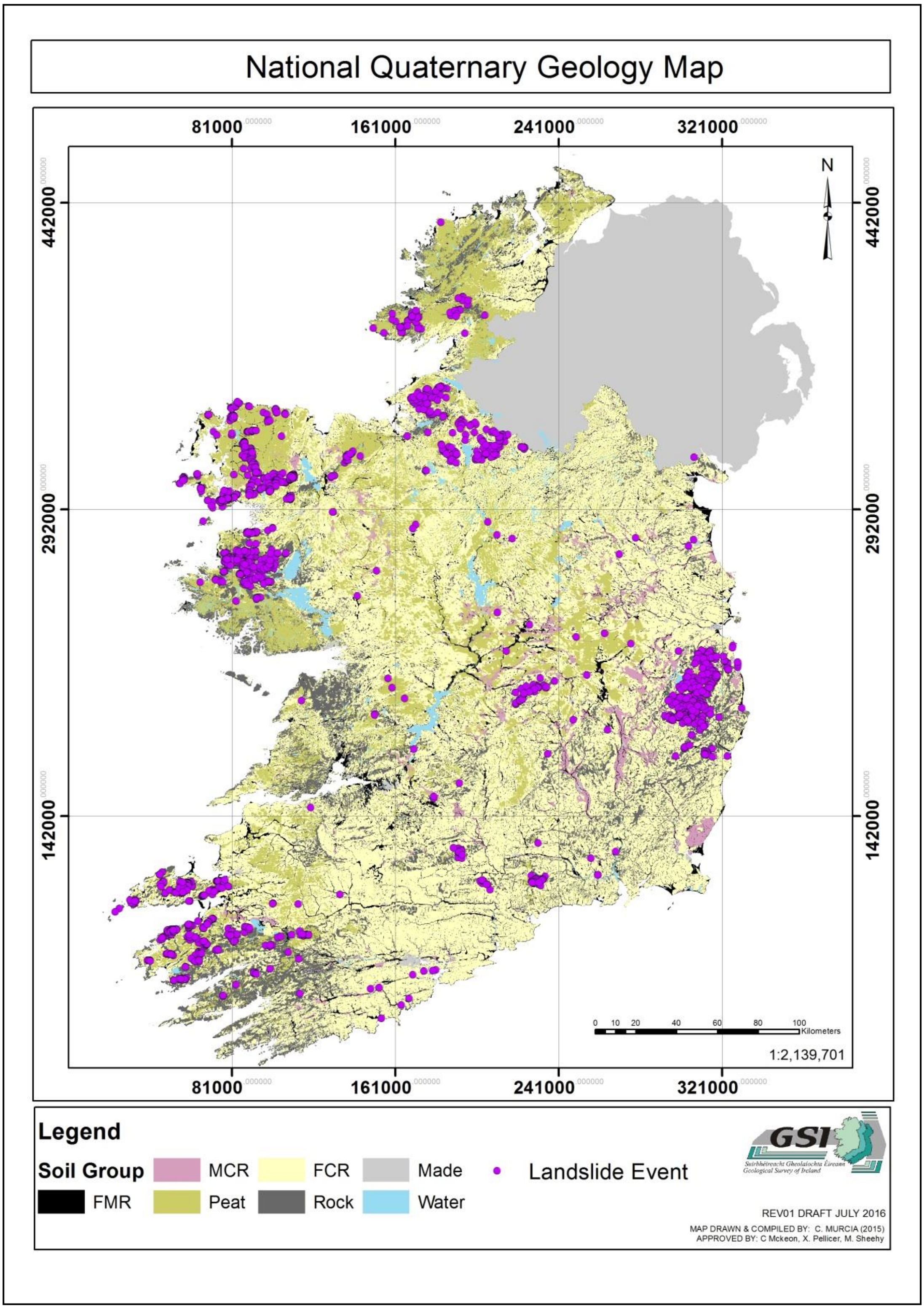


Figure A4: UCU Soil Classification Map

Table A1: Soil Group Descriptions

FMR	These are **F**ine to **M**edium **R**ange grain size soils. Typically the 'fine' end of this range is characterised by silts and at the 'medium' end by fine sand.	**MCR**	These are **M**edium to **C**oarse **R**ange grain size soils. Typically the 'medium' end of this range is characterised by sands and gravels and at the 'coarse' end by cobbles and boulders. They are often found adjacent to FMR but at higher elevations on the valley sides.
FCR	These are **F**ine to **C**oarse **R**ange grain size soils and due to their wide variation in size distribution it is not possible to assign these to one or other of the above categories. The predominant material is glacial till which can range from fine clays to large cobbles in a matrix of finer material.	**RNS**	This abbreviation is for **R**ock **N**ear **S**urface and means that the soil is thin with rock less that a metre below the surface or in fact exposed. They are most extensive at high elevations but are also found along some coastal strips and incised valleys. They may be of glacial till origin or in-situ weathered materials and may consist of fines, sands and larger cobles in varying proportions, but can also comprise thin organic soils tending towards peat.
Peat	Peat has unique properties and as such has been categorised separately. This category largely consist of peat (or turf) as would normally be recognised and occurs as blanket peat in upland areas but also to a much lesser extent may comprise other highly organic soils in low lying marshlands.	**Made**	Made ground refers to areas where engineered construction has been undertaken and mainly encompasses urban areas but also includes large embankments at reservoirs and similar structures.
Water	Loughs and Lakes and includes natural and manmade impoundments.		

The topographic flow index is computed from the DTM. The process considers each grid cell in turn and working uphill determines all cells that can flow towards to recipient cell. This gives the contributing area, but in making this aggregation each contribution cell is weighted by its slope. The range of values has been partitioned into three zones of equal area (across the study area as a whole).

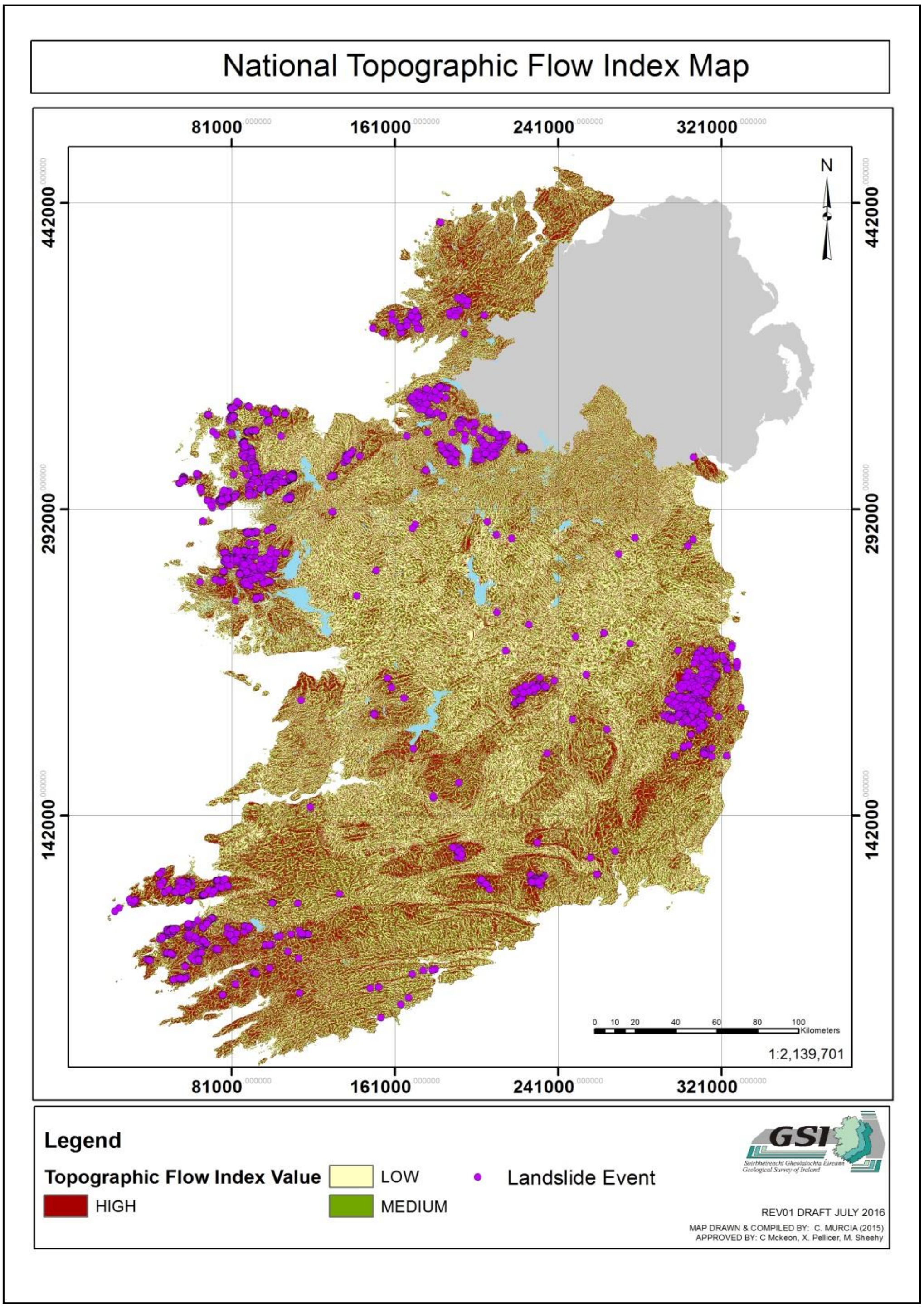


Figure A5: UCU Topographic Flow Index Map

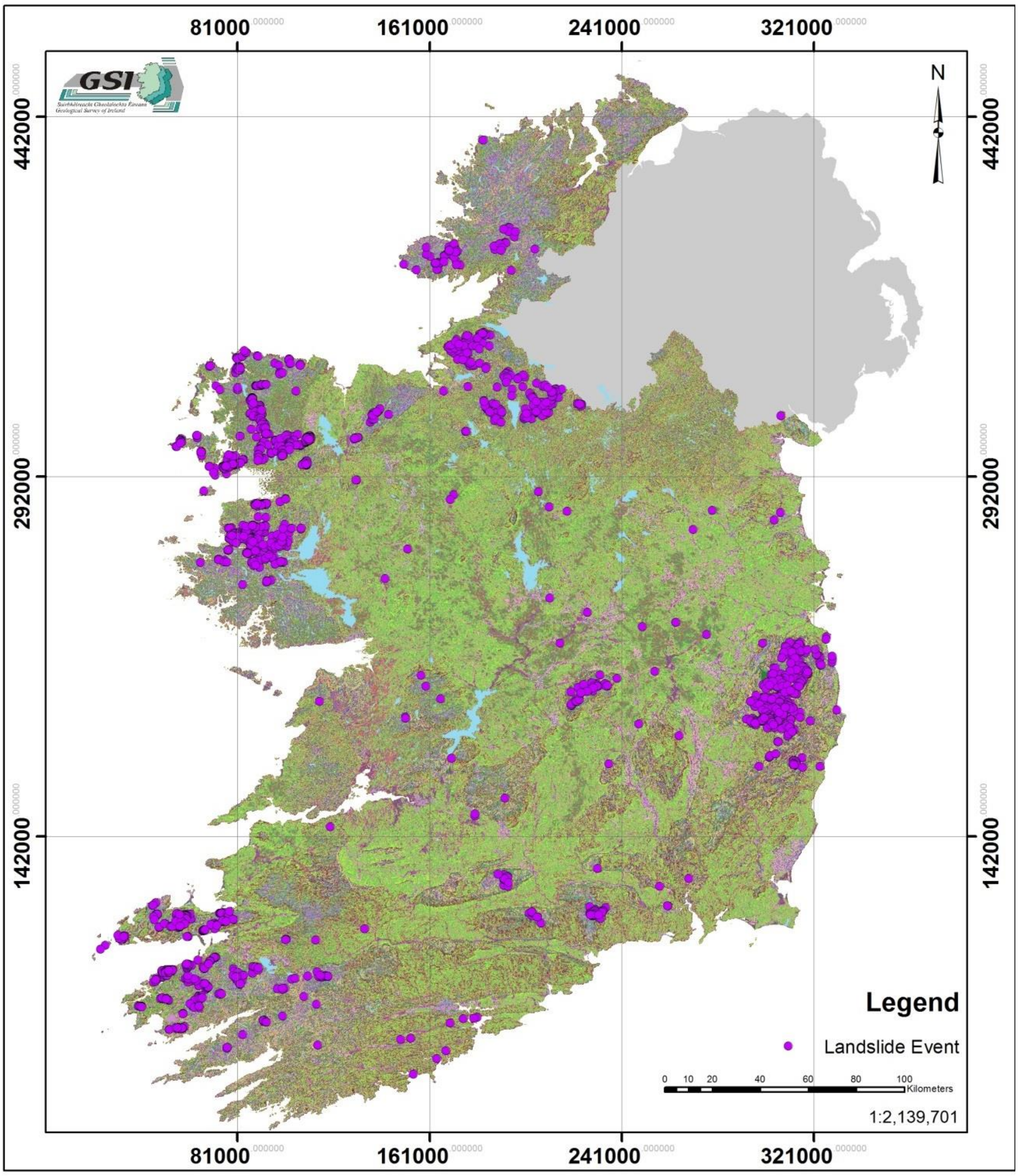


Figure A6: UCU Combination of Slope, Soil and TFI mapping

In this illustration all three variables have been combined to create Unique Condition Units (UCU).

135 out of a possible 168 combinations of these UCU's are represented nationally. Analysis was performed using the UCU's to count the numbers of landslides falling into various UCU's.

Table A2: Count of landslides by slope, soil type and TFI.

Soils	TFI	0-3	3-6	6-10	10-15	15-20	20-30	30-45	45-65	Grand Total
FCR	1	3	4	2	3	3	0	0	0	**15**
	2	6	3	15	5	5	14	3	0	**51**
	3	7	11	25	47	34	65	9	0	**198**
FCR Total		16	18	42	55	42	79	12	0	264
FMR	1	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0
	3	4	1	0	1	0	0	0	0	6
FMR Total		4	1	0	1	0	0	0	0	6
MCR	1	1	0	1	4	1	0	0	0	**7**
	2	0	1	1	2	2	2	2	0	**10**
	3	1	1	4	21	28	31	14	0	**100**
MCR Total		2	2	6	27	31	33	16	0	117
Peat	1	25	36	24	11	5	5	0	0	**106**
	2	12	33	46	45	30	20	2	0	**188**
	3	19	41	68	70	44	28	5	0	**275**
Peat Total		56	110	138	126	79	53	7	0	569
RNS	1	3	8	15	26	40	66	10	0	**168**
	2	0	2	11	35	54	180	215	6	**503**
	3	0	3	24	69	133	303	355	31	**918**
RNS Total		3	13	50	130	227	549	580	37	1589
Grand Total		**81**	**144**	**236**	**339**	**379**	**714**	**615**	**37**	**2545**

This table gives the basic break-down of the numbers of landslides occurring within UCU's.
There are several gaps in the table. In part this is because some combinations of UCU do not occur area (greyed out) but also because some UCU's have no recorded landslide events.

Table A3: Areas (Km2) of UCUs by slope, soil type and TFI.

Soils	TFI	0-3	3-6	6-10	10-15	15-20	20-30	30-45	45-90	Grand Total
FCR	1	11620	2555	929	151	8	1	0	0	15264.01
	2	6922	3489	1639	405	56	15	1	0	12526.52
	3	5745	3189	1741	595	132	42	4	0	11447.95
FCR Total		24288	9233	4308	1151	196	58	5	0	**39238.47**
FMR	1	692	28	7	1	0	0	0	0	728.35
	2	493	42	10	2	0	0	0	0	548.23
	3	1548	206	44	8	1	0	0	0	1806.13
FMR Total		2733	277	61	10	1	0	0	0	**3082.71**
MCR	1	1099	147	38	6	1	0	0	0	1291.78
	2	504	110	38	16	7	5	1	0	681.49
	3	457	98	48	49	35	29	7	0	724.39
MCR Total		2061	355	125	71	44	34	8	0	**2697.66**
Peat	1	3888	565	226	60	9	2	0	0	4750.31
	2	2316	771	503	221	58	16	1	0	3885.62
	3	2805	942	614	306	88	26	1	0	4782.07
Peat Total		9009	2278	1344	587	154	44	2	0	**13418.00**
RNS	1	1320	828	577	280	91	44	5	0	3144.81
	2	499	616	790	686	381	295	96	3	3366.23
	3	396	431	610	702	480	431	169	8	3226.78
RNS Total		2215	1874	1978	1667	953	770	269	11	**9737.81**
Grand Total		**40305**	**14017**	**7816**	**3487**	**1348**	**906**	**284**	**11**	**68174.65**

This table gives the land coverage of each of the UCU's in the study area.

The predominant area is in the slope category 0-3 degrees and thereafter there is a fairly rapid decline in coverage with increasing slope.

Table A4: Landslide incidence by slope, soil type and TFI

Soil	TFI	0-3	3-6	6-10	10-15	15-20	20-30	30-45	45-65	Grand Total
FCR	1	0.03	0.16	0.22	1.99	36.44	0.00	0.00	0.00	0.10
	2	0.09	0.09	0.92	1.23	8.98	92.86	295.86	0.00	0.41
	3	0.12	0.34	1.44	7.90	25.75	155.01	236.37	0.00	1.73
FCR Total		**0.07**	**0.19**	**0.97**	**4.78**	**21.43**	**135.95**	**246.77**	**0.00**	**0.67**
FMR	1	0.00	0.00	0.00	0.00	0.00	0.00			0.00
	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
	3	0.26	0.49	0.00	13.29	0.00	0.00	0.00		0.33
FMR Total		**0.15**	**0.36**	**0.00**	**9.96**	**0.00**	**0.00**	**0.00**	**0.00**	**0.19**
MCR	1	0.09	0.00	2.60	67.09	121.89	0.00	0.00	0.00	0.54
	2	0.00	0.91	2.63	12.49	27.40	40.87	165.84	0.00	1.47
	3	0.22	1.02	8.25	42.52	79.13	107.39	195.71	0.00	13.80
MCR Total		**0.10**	**0.56**	**4.80**	**37.83**	**71.26**	**97.30**	**191.05**	**0.00**	**4.34**
Peat	1	0.64	6.37	10.60	18.36	57.17	265.39	0.00	0.00	2.23
	2	0.52	4.28	9.14	20.36	51.90	127.40	245.82	0.00	4.84
	3	0.68	4.35	11.07	22.89	50.08	107.12	419.89	0.00	5.75
Peat Total		**0.62**	**4.83**	**10.27**	**21.47**	**51.17**	**121.22**	**337.97**	**0.00**	**4.24**
RNS	1	0.23	0.97	2.60	9.29	43.87	151.39	204.47	0.00	5.34
	2	0.00	0.32	1.39	5.10	14.16	60.93	224.55	180.16	14.94
	3	0.00	0.70	3.93	9.83	27.70	70.30	210.64	397.19	28.45
RNS Total		**0.14**	**0.69**	**2.53**	**7.80**	**23.83**	**71.29**	**215.47**	**331.92**	**16.32**
Grand Total		**0.20**	**1.03**	**3.02**	**9.72**	**28.12**	**78.80**	**216.18**	**325.96**	**3.73**

This table has been produced by dividing the landslide numbers by the corresponding area for each UCU. The landslide density values have been scaled up to be expressed as landslides/100 km^2. The lower line (titled "Grand Total") which is based on the aggregated totals by slope categories alone shows a rapidly increasing rise from close to zero to over 325 landslides/100 km^2. Within the body of the table there are variations in landslide density dependent upon soil group and TFI.

The information in this table can be reformatted to rank the UCU's and produce a thematic map of low to high landslide susceptibility. However, parts of the map for which there is no data would be blank unless values are extrapolated.

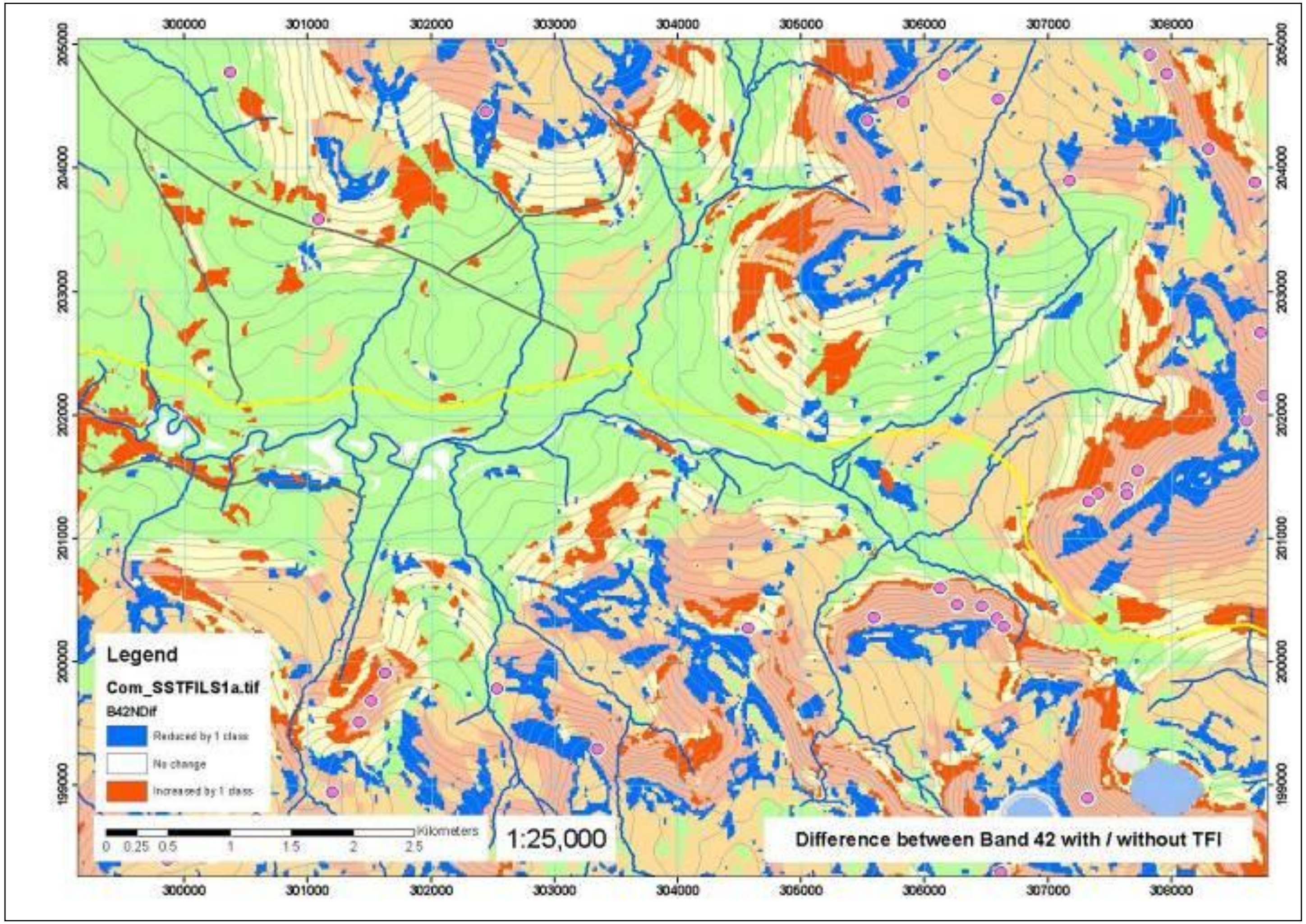
Table A5: UCU Categories for a four band classification scheme

Soils	TFI	0-3	3-6	6-10	10-15	15-20	20-30	30-45	45-65	Grand Total
FCR	1	D	D	D	D	D	Ci	Ci	Bi	**15**
	2	D	D	D	D	C	C	B	Bi	**51**
	3	D	D	D	C	C	B	B	Ai	**198**
FCR Total		16	18	42	55	42	79	12	0	264
FMR	1	Di	Di	Di	Di	Di	Di	Ci	Ci	0
	2	Di	Di	Di	Di	Di	Ci	Bi	Ci	0
	3	D	D	Di	D	Ci	Ci	Bi	Bi	6
FMR Total		4	1	0	1	0	0	0	0	6
MCR	1	D	Di	D	C	B	Bi	Ai	Ai	**7**
	2	Di	D	C	C	B	A	A	Ai	**10**
	3	D	C	C	B	B	A	A	Ai	**100**
MCR Total		2	2	6	27	31	33	16	0	117
Peat	1	D	C	C	B	B	A	Ai	Ai	**106**
	2	D	C	B	B	A	A	A	Ai	**188**
	3	D	C	B	A	A	A	A	Ai	**275**
Peat Total		56	110	138	126	79	53	7	0	569
RNS	1	D	D	C	B	B	A	A	Ai	**168**
	2	Di	C	B	B	A	A	A	A	**503**
	3	Di	C	B	B	A	A	A	A	**918**
RNS Total		3	13	50	130	227	549	580	37	1589
Grand Total		**81**	**144**	**236**	**339**	**379**	**714**	**615**	**37**	**2545**

This table shows the distribution of the susceptibility banding from Low (D) to High (A) and also where inferred values (greyed out values) have been placed to ensure areas where either the UCU doesn't exist or no landslides have been recorded are included in the national classification scheme.

Table A6: Description of Landslide Susceptibility Bands

Category	Description	Physical Geography	Landslide Incidence	Number	Area
A	High	The predominant soil type is Rock Near the Surface and to a slightly lesser extent Peat. Slopes are mainly in the 20-30º band with the remainder falling into bands 15-20º and 30-45º range and occasionally much steeper.	The highest number of landslides occurs in the 30-45º rock near surface class. The highest density can be seen in the 30-45 º range for peat and to a slightly lesser extent in rock near surface within the same slope range.	63%	3.5%
B	Moderately High	The predominant soil type is Rock Near the Surface and to a lesser extent Peat and Medium to Coarse. Slopes are mainly in the 10-15º band with a significant proportion in the 6-10º and 15-20º range.	The highest number of landslides occurs in the 10-15º Rock Near the Surface class. The highest density is in the 30-45º Fine to Coarse class..	19.5%	7%
C	Moderately Low	The predominant soil type is Medium to Coarse and to a slightly lesser extent Fine to Coarse Range, Rock Near Surface or Peat which occur in equal proportions. Slopes are mainly in the 3-6º band with a significant proportion in the 6-10º range.	The highest number of landslides occurs in the 3-6º Peat class. However the highest density is in the 20-30º Fine to Coarse Range class, but these conditions are extremely limited in extent.	11.5%	7.5%
D	Low	The predominant soil type is Fine to Coarse Range material followed by Medium to Coarse Range material which together exceeds all others by a significant extent. Slopes are mainly in the lower ranges of 0-3º , 3-6º and 6-10º range	The highest density of landslides is in the steeper 15-20º Fine to Coarse Range class, although in numbers relatively few slides. The most common characteristics are slopes of 0-3º in Fine to Coarse Range soils but these conditions are generally devoid of landslides.	6%	82%



This illustration covers the same geographical location as the individual slope, soil and TFI maps shown above and used in the generation of the landslide susceptibility map.

In this figure the background susceptibility band classification colours have been muted so as to accentuate changes due to the TFI variable.

The areas in red are where the inclusion of the TFI has increased the susceptibility by one band increment. Conversely the blue areas have been reduced by one band increment. The red tends to be in steep concave topography and the blue in flatter convex areas such as broad spurs and above the upper break of slope.

Figure A7: Changes to Susceptibility Bands due to the influence of TFI

Appendix B

The following appendix provides a series of illustrations of historic and recent landslides in a variety terrains

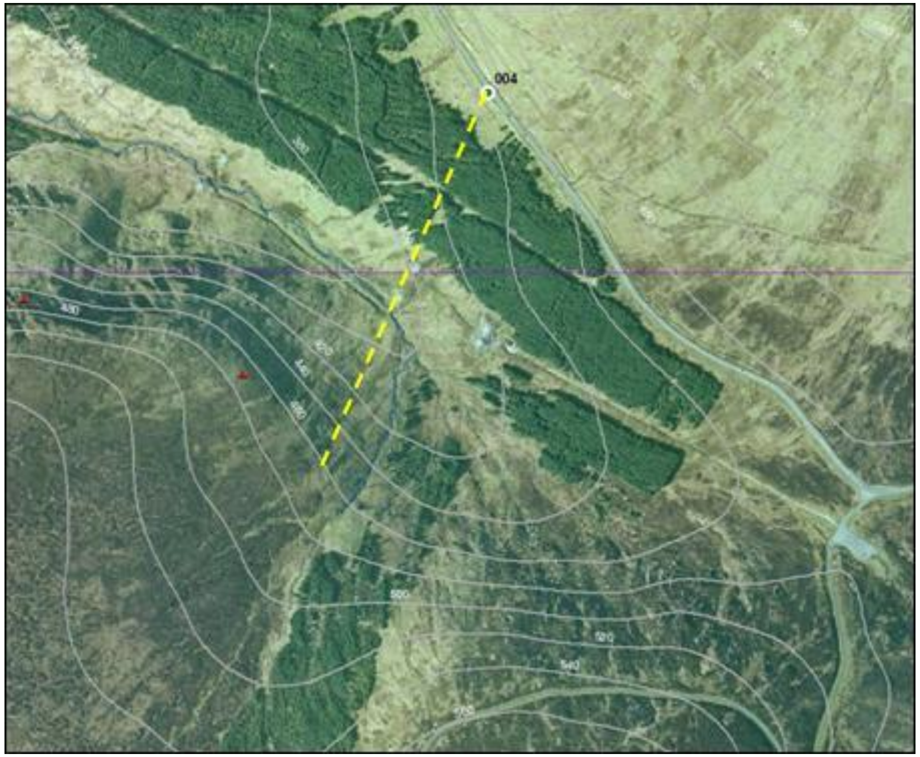
Grid references are approximate and given to four digits easting and northing

Figure B1: Small recent debris slide

Grid Ref: 3010 1913

This is an unmistakable small 'classic' landslide with a clear rounded head scarp, a dished main body and material bulged up at the toe. All elements from head scarp down to the toe are clearly visible. Note change in vegetation below toe (and at western yellow point on map) which is indicative of locally different drainage conditions that predated the slide. The landslide is on a steep sided valley and positioned well down the slope towards the transition to the bottom of slope. Other older landslides scars are visible within the general locality. The IFSPM map shows the location to be at the transition between Rck (rock within a metre of the surface) and TLPSsS (a till). The exposed material is a glacial till of angular / semi rounded cobbles through coarse gravels down to fines.

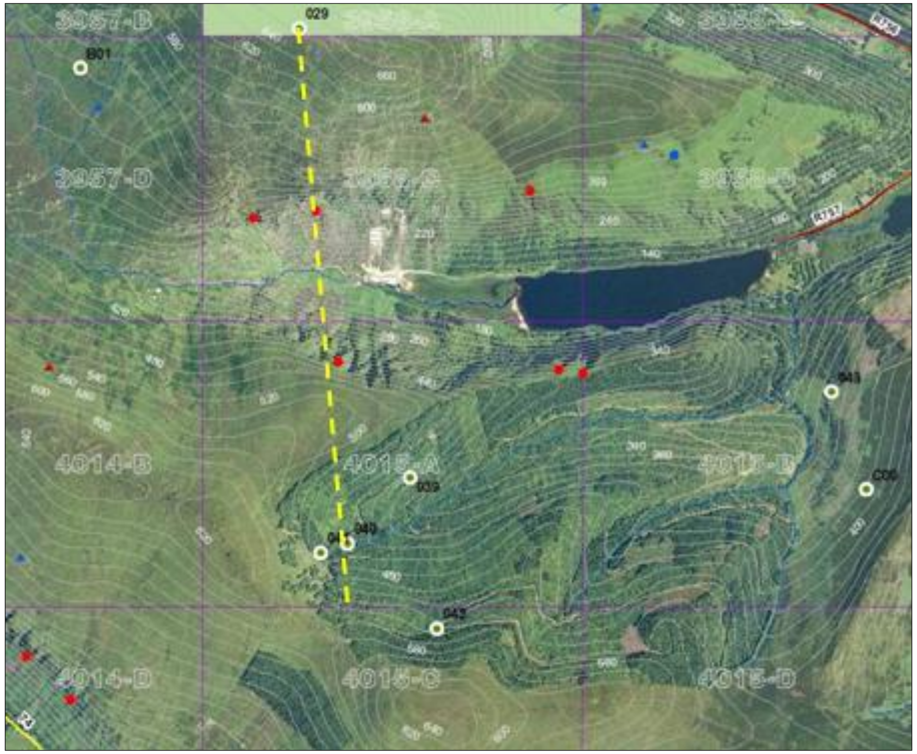
Figure B2: Small recent debris slide - seen from a distance



Grid Ref: 3067 2002

This landslide was opportunistically identified from a distance of 600m. Although not inspected in-situ, it is clearly a fairly recent debris slide starting at the break of slope. A sharp head scarp is visible, but there is not a distinct toe as the steep gradient means that the material has spread and dispersed well down the slope with the lower level being obscured by trees. Older slides, now revegetated, are visible along the break of slope towards the stream on the left. The IFSPM map shows the location to be at the transition between Rck (rock within a metre of the surface) and BktPt (blanket peat) at the higher elevations. The appearance and behaviour of the slide is more characteristic of a coarse till, which may well be the material represented by the Rck label.

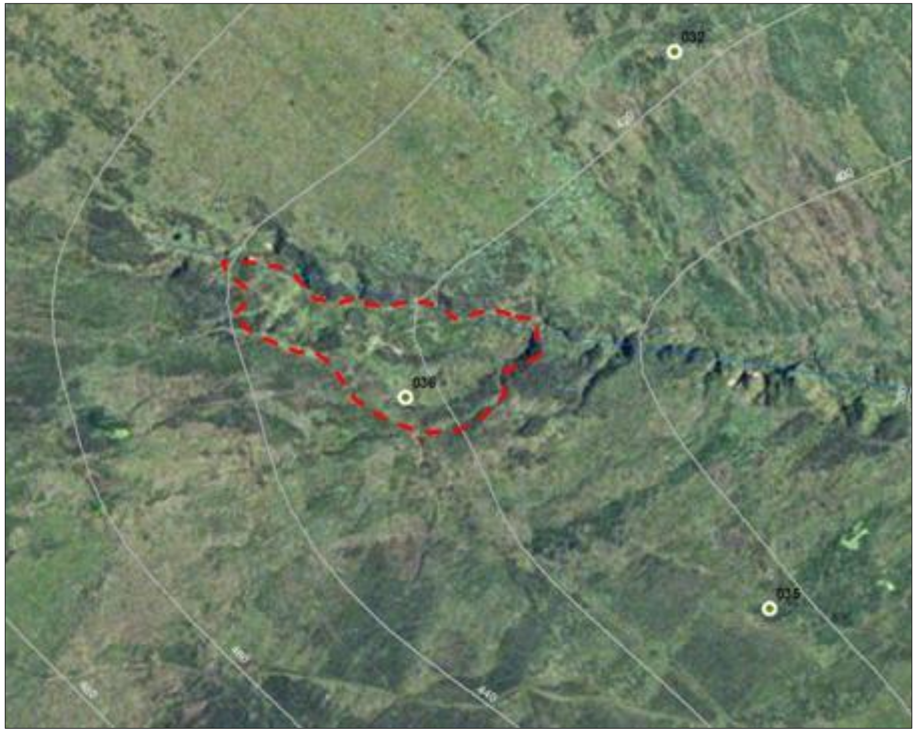
Figure B3: Major recent debris slide - seen from a distance



Grid Ref: 3088 1945

This landslide was identified from a distance of 3000m. Although not inspected in-situ some closer observations were made. It is a fairly recent and large slide which does not show on the 2005 aerial photo. The IFSPM map shows the location to be Rck (rock within a metre of the surface) and so in fact this is likely to have been a debris slide. The underlying bedrock is visible and is dipping steeply in the direction of the slide. In topographic terms the head of the slide lies on the break of slope in a saddle between two hills, so is likely to be a convergence point for surface and groundwater flows. Toe and lower levels are obscured by the shoulder of a closer hill. Forestry tracks at lower levels were clear so it is expected that there will be a large build up of debris and trees (possibly unstable) at an intermediate elevation.

Figure B4: Old river terrace collapse



Grid Ref: 2963 1888

This is a fairly typical river terrace collapse which has been triggered by undercutting at the toe. This was identified in the field while transiting to other points. The terrace collapse is difficult to see on the aerial photos due to 'flat' lighting and a mosaic of vegetation changes. Two head scarps were identified. The second (lower) slide could have been contemporary with the larger movement or considerably later. The toe material has been flushed out by stream flow. The slide is old as there is now no differentiation between the vegetation within the body of the slide and the immediate surrounding area.

Figure B5: Ancient very large debris slide

Grid Ref: 3043 2123

This slide could easily be missed due to its large size and loss of sharp features. It was identified as a candidate landslide from the aerial photography. The contours provide an indication of loss of material and there is no watercourse or other explanation for a depression in what is otherwise a very uniform hillside. The OSi 2000 aerial photo shows a more distinct shadow due to a lower sun angle. Furthermore the OSi 1995 B&W photo (possibly infrared) shows a secondary landslide shaped feature lying within the main landslide on its eastern margin. The shallow dished area in the main body of the landslide is visible (as in terrestrial photo) but the toe is not obvious, although at one time there must have been a considerable volume of material. The only hint of a toe is now in the somewhat anomalous counter-trend contour at the foot of the slope. These are 20m interval contours thus a higher resolution examination of the DTM may reveal more.

Figure B6: Large peatslide recorded in 1937

Grid Ref: 3025 2050

Identified from aerial photography but, unknown to photo-interpreters, this peatslide which occurred in 1937 was already in the GSI database. Note the type and degree of re-vegetation and texture / colour differentiation on the aerial photo. (The top western point although of similar colour and texture on the aerial photo proved not to be a landslide but had many tension cracks.) It is instructive to see the extent of revegetation that has occurred in the last 84 years. If it was not for the contrast above and below the scarp line there are few indications of a slide at this point. However, further downslope there are peat blocks now somewhat rounded. The scarp profile itself is similar to that in peat haggs – except here there are no haggs thus this feature stands out as anomalous.

Figure B7: Old peatslide of unknown date

Grid Ref: 313660 211590

This candidate location was identified from aerial photography. This is a long (c.350m) linear peatslide with well-defined edges although these have now 'softened' through erosion and age. The peatslide commenced on a fairly shallow slope at a feature that appears to be the remnants of a collapsed peat pipe. The peatslide is probably of considerable age as the scar area is now well revegetated, but jumbled blocks of peat within the main scar are still visible. Some 800 metres to the north-northwest of this location there are other peatslides and an area with large semi-circular tension cracks in the peat with standing water close to the surface.

Appendix C

The following appendix provides a listing of all relevant reports produced throughout the Landslide Susceptibility Mapping project

Landslide Susceptibility Mapping – Methodology development

Geological Survey Ireland, Mouchel. 2011. Landslide Susceptibility Mapping: Literature Review and Findings

Geological Survey Ireland, Mouchel. 2012. Landslide Susceptibility Mapping: Developing a Surface Flow Hydrology Index.

Geological Survey Ireland, Mouchel. 2012. Landslide Susceptibility Mapping: Sensitivity and Consistency Checks.

Geological Survey Ireland, Mouchel. 2012. Landslide Susceptibility Mapping: Classifying Landslide Susceptibility.

Geological Survey Ireland, Mouchel. 2013. Landslide Susceptibility Mapping: Unique Condition Units: Theory and Practice

Landslide Susceptibility Mapping – Inventory development

Geological Survey Ireland, TCD. 2014. Inventory of landslides in County Kerry and County Mayo

Geological Survey Ireland, GDD. 2014. Landslide inventory Mapping – South Donegal.

Geological Survey Ireland, GDD. 2014. Landslide inventory Mapping – Slieve Bloom.

Geological Survey Ireland, GDD. 2014. Landslide inventory Mapping – South Tipperary.

Geological Survey Ireland, GDD. 2014. Landslide inventory Mapping – West Galway