Landslide susceptibility mapping in North-East Wales

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Abstract

In North-East Wales, United Kingdom, slope instability is a known environmental hazard causing significant damage to the built environment in the recent past. This paper reports on the creation of a digital landslide inventory for North-East Wales and the use of a Geographical Information System (GIS) to create landslide susceptibility models that are applicable to landslide hazard management in the area. The research undertaken has resulted in the most comprehensive landslide inventory of North-East Wales to date, documenting 430 landslides within the area. Landslide susceptibility models created within a Geographical Information System (GIS) using a statistical (multiple logistic regression) approach, divide the landscape of North-East Wales into areas of ‘low’, ‘moderate’ and ‘high’ landslide susceptibility using calculated probability values. These models indicate that 8% of the surface exposure of drift deposits and 12% of the area of solid geology is of high or very high susceptibility to slope instability. Validation tests have demonstrated the accuracy of these models and their potential value in a predictive sense. The digital landslide database and susceptibility models created are readily available to interested stakeholders, and may be useful tools in land-use planning, development of civil contingency plans and as guidance for the insurance industry.

1. INTRODUCTION

The *Review of Research on Landsliding in Great Britain* (Jones and Lee 1994) demonstrated that slope instability is a significant natural hazard in the United Kingdom. North-East Wales, United Kingdom (UK) (see Figure 1) was one of the regions highlighted as having a very high incidence of slope instability. Whilst landslide assessment at a regional scale has been carried out for other regions in the UK with a high incidence of landslides (Conway *et al*. 1980, Thurston 1997), no such research has been done for North-East Wales. As indicated by Nichol *et al.* (2002) slope instability is of concern in North-East Wales, with numerous landslides causing damage to public transport networks and properties after heavy rainfall. Over the last 10 years there has been an increase in the number of reported landslides in this region. A large number of the landslides in North-East Wales are believed to be relict landslides that were formed during postglacial conditions, 8,000 to 10,000 years ago, after the Devensian glaciation (Warren 1984). While most of these landslides are generally stable under current environmental conditions, some of them have been reactivated in the recent past, for example the landslides at Llanddulas (Smith 2002) and Chirk (Norbury 2002). The landslides have been reactivated by changes in land-use patterns and more frequent and intensive rainfall (Nichol *et al*. 2002). With the possible threat of human induced climate change, which may result in warmer wetter winters and more varied and intense rainfall (Arnell and Reynard 1996, Collison 2000, Environmental Agency 2007), the reactivation of relict landslides and the triggering of new landslides is a concern (Nichol 2002). There is therefore a need to understand where existing landslides are and where future landslides are likely to occur as well as the impact they are currently having on the built environment.

The research presented herein involves: a comprehensive inventorying of landslides within the study area at a regional scale; the creation of landslide susceptibility models and the detailed study of the impact of slope instability on the built environment within a selected section of the study area.

*Insert Figure 1 here

Within the UK it has been recognised and accepted that there are two distinct mode of occurrences of landslides (see Conway *et al*. 1980, Thurston 1997), those in recent (quaternary) glacial sediments, which in the UK are termed 'drift geology' and those is what is termed 'solid geology' (lithified material). These terms have been adopted throughout this paper. The geology of the area has been divided into solid geology (see Figure 2) and drift Geology (see Figure 3) and landslides analysis in the two undertaken separately. In 'solid geology', a variety of lithologies may be recognised within the study area. Most of the rocks are mudstones/shales, sandstones, limestones and volcaniclastics (see Figure 2). The mudstones/shales are of Ordovician, Silurian and Carboniferous age, the limestones and volcaniclastics are predominantly of Carboniferous age and the sandstones mostly Permo/Triassic (BGS 2003a). The drift deposits covering the land surface of North-East Wales are predominantly of riverine, lacustrine, aeolian, tidal and glacial origin. Of the deposits, those of glacial origin dominate, making up over 70% of the drift deposits in the study area (see Figure 3).

*Insert Figures 2 & 3 here

2. Landslide inventorying, susceptibility modelling and impact survey

Landslide hazard assessment at a regional scale involves the identification of areas of past and present instability, and use of this information to quantitatively predict the spatial distribution of future landsides (Guzzetti *et al*. 1999). In landslide prone areas, landslide hazard assessment provides a scientific basis for the implementation of land-use, emergency management and loss reduction measures (Haubin *et al*. 2005).

Geographical Information System (GIS) was used for landslide susceptibility assessment. GIS offers the ability to manipulate (quickly and efficiently) and output significant volumes of data for large geographical areas. A combination of GIS-based direct and indirect landslide hazard assessment methods was used to create landslide susceptibility models for the study area (see Chung and Fabbri, 1995, Guzzetti *et al*. 1999, Pistocchi *et al.* 2002). The direct mapping involved data collection through the use of aerial photography and field mapping to create a landslide inventory database. The indirect component involved the use of statistics to make informed decisions about the susceptibility of non-landslide areas to future instability. The stages involved in the slope evaluation for this were; Landslide inventorying and digital database creation; Determining factors controlling the distribution of landslides, weighting and combining the relevant factors to create susceptibility and validation of the model (see Figure 4).

*****Insert Figure 4 here

2. 1 Landslide inventorying

A number of methodologies were considered and adapted to create a new landslide inventory in order to enhance the existing landslide database,. These were: review of existing published and unpublished literature; aerial photo interpretation, and geological/geomorphological field investigation. A review of secondary data was carried out on landslide data from The British Geological Survey (digital and hardcopy maps) (BGS, 2003a, 2003b and 2004), newspaper articles, geotechnical reports from local consultancy companies/local government organisations and published papers and books (Smith and George 1961, Ager 1992, Nichols *et al*. 2002, Davis *et al*. 2004).

2.1.1 Aerial photograph and field mapping

Satellite and airborne digital has been used with success to map landslides in the UK (Wilson 2006, Browitt *et al.*, 2007, Culshaw *et al*. 2007, Whitworth *et al*. 2005). Landslides were mapped by examining 1:10,000 scale vertical aerial photographs obtained from local county councils (Flintshire, Denbighshire and Wrexham (borough) councils). Just over 5,000 stereo pairs of aerial photographs were examined and interpreted for this research. Aerial photograph interpretation was used mainly to map the location and spatial extent of landslides and where possible, the landslide type and impact on the built/natural environment.

Field verification and mapping were carried to assess the reliability and accuracy of landslide location, type, geomorphic setting and lithology, as determined from the aerial photograph interpretation. Together this allowed an attribute table to be compiled that included: landslide type; relative age; activity; geology; possible trigger mechanism (where possible); and, whether it has a reactiviated slide. As a guide, the system of landslide recognition proposed by EPOCH in 1993 and presented in Dikau *et al.* 1996, pp.8-9) was used a guideline for the recognition of landslide types within the study area.

2.1.2 Landslide database

Based on the aerial photograph interpretation and field mapping, 186 additional landslides were identified, that together with the 244 recorded by the British Geological Survey (BGS 2004, 2003a & 2003b) amount to 430 landslides in the updated landslide database (including information on: landslide type; relative age; activity; geology; possible trigger) and impact) for North-East Wales (see Figure 5). These landslides cover an area of approximately 24 km^2 in total representing approximately 1% of the total land surface of the study area.

Analysis of the final landslide inventory indicates that the minimum recorded area for a landslide is 298 m^2 and the maximum is 1,542,776 m^2. The mean area is 54,533 m^2 and the modal value is 403,332 m^2 (Figure 6). Most of the landslides are between 10,000 m^2 and 100,000 m^2, however, some are very large in size and are over 1,500,000 m^2, contributing to the large standard deviation of 125162.24. The large standard deviation is an indication of the diverse nature of some landsides and the diversity of the factors that are contributing to their occurrences.

*Insert Figures 5 and 6 here

2.2. Landslide Type

The ‘landslide type’ attribute is a description of the general type of landslide based on the EPOCH (1993) classification of landslides (see Table 1). Translational or single rotational slope failures dominated within the study area (see Table 1). The translational landslides were generally shallow slides (>3m) occurring in both drift and solid geology. In drift geology the landslides mostly occurred in clay and/or sand of glacial origin (see Figure 7), for example, the Panorama landslide, Eglwyseg Mountain (e.g. at GR:324429,343018) (Ward, 2002). Translational slides solid geology have three main modes of occurrence, these are: in the upper weathered surface of solid rock, for example the Pwll Melyn landslide at Holywell (GR:302509,377424) (Nichol 2002b), in highly jointed rocks, particularly where jointed blocks are dipping (‘daylighting’ or sloping) down slope (GR:303546,371373) and as reactivated slides within the debris of older relict landslides (GR: 324429,343018).

Insert Table 1 here

*Insert Figure 7 here

Rotational slides also occur both in drift and solid geologies. In the drift geology, the larger slides (>10m in width) are typically multiple rotational, relict and mostly inactive. However, there are few relatively deep-seated multiple rotational large landslides, for example, the Trevor landslide (GR:326887,342672) (Nichol and Graham, 2002), which is active. The smaller rotational slides (<10m in width) are generally, single rotational slides and active. Some are reactivated relict landslides, for example, the Eglwyseg Mountain landslide (GR:324429,343018) and other are ‘first time’ landslides for examples Vivod landslides at Llangollen (GR:303546,371373) (Reynolds Geo-sciences 2002a). Where rotational landslides occur within solid geology, these are characteristically very large (scarps > 100m in width). These large landslides are mostly multiple rotational slides, relict in age, and generally inactive. Exceptions to this pattern include the landslides at Holywell (GR:318507,376321) and Greenfield (GR:319437,377591), both of which are slow moving landslides located in close proximity to urban areas.

Complex landslides are rare in the study area. The Trevor Chirk and Llanddulas landslide (GR:326887,342672; 329827,340943; GR:292669,378204)) (Norbury 2002, Smith 2002) are examples of such type of landslide.

Flows in the study area normally occur as part of a translational or rotational slide. Most of these flows are either debris flows or mudflows, where the initial movement took place in boulder clays. The Pentredwr landslide at Horseshoe Pass, Llangollen resulted in a debris flow that travelled a distance of 240m downslope, blocking the Pentredwr Road with debris up to 2.5m deep over a length of 35m (Nichol and Seedhouse 2002). In addition, the debris continued down to the river blocking it and forming a landslide dam, which was breached leading to flooding downstream of the dam. The Nant Wood Landslide (Reynolds Geo-sciences 2003b) moved a significant amount of debris, which is believed to have blocked the Nant River (Reynolds Geo-sciences 2003b). There are few landslides that are recorded exclusively as flows (i.e. GR:315765, 365964). Generally, unless these are recent landslides little evidence is preserved that may contribute to an underrepresentation of this landslide type.

2.2.1 Landslide Trigger Mechanism

Triggering mechanisms are those events/processes that change a slope from being marginally stable to being unstable, resulting in failure. Triggering mechanisms commonly cited as being responsible for slope failures within the study area include: rainfall, river undercutting and human influences (Nichol 2002a).

North Wales has one of the highest rainfall intensities and snow day frequencies in the UK (Hulme and Barrow 1997), which both contribute to the length of time that slopes are saturated, thereby contributing to slope instability within the area. Rainfall appears to be the dominant trigger mechanism within the study area. This was evident after the rainfalls of 2000, when a large number of landslides were triggered (Nichols *et. al*. 2002). The Pentredr landslide at Horseshoe Pass (Nichol and Seedhouse 2002), the Ty' n-y-Coed landslide at St Asaph (Strathan and Ward 2002) and the Wigfair road landslide, Trefant (Heald 2002) are examples of a few of the landslides triggered during the heavy rains of 2000. Most of the landslides reported by Nichols *et al*. (2002) were believed to be associated with rainfall. In most cases it is believed that the rainfall acted to increase the pore water pressure in the rock or soil, which reduced the shearing resistance of the material Nichols *et al*. 2002). This may happen in a number of ways, rainfall may raise the level of the water in an existing aquifer up into a susceptible layer, or it may create a perched water table in the susceptible layer, for example the Eglwseg Mountain landslide (Ward 2002). In this particular landslide a susceptible permeable layer overlies an impervious layer. Build up of pore water pressure in the susceptible layer caused it to fail. Pore pressure may also build up in the susceptible layer when water enters it and cannot escape or escape quickly enough. The large rotational failure at Llandulas (Smith 2002) is in some way related to a rise in pore water pressure caused by water from the sea rising up through the underlying limestone.

Undercutting by rivers is commonly cited as being a principal trigger of slope failure within the study area (Warren, *et al*. 1984, Nichol *et al.* 2002, Nichol and Seedhouse 2002, Davis *et al.* 2004). As Warren *et al.* (1984) noted, landslides are common on the valley sides of the study area that have been undercut by the rivers. One example of a landslide occurring as result of river undercutting is at Chirk, where the action of the River Dee contributed to reactivation of a large relict landslide (Norbury 2002). Undercutting by erosive agents removes lateral support and increases the slope angle (oversteepening), both of which increase the shear stress in the slope causing it to fail. River undercutting is recognised as the present day dominant erosional agent in the study area, removing lateral support and oversteepening slopes. However, glaciers and fluvio-glacial outwash rivers in the past have played a significant role in oversteepening slopes. This led to a number of landslides during the early postglacial period, and probably accounts for the number of relict slides within the study area (Davis *et al*. 2004).

'Human' triggering is normally one of the main causes of slope instability (Jones 1993) in the UK. Fortunately there are not many recorded instances where human influence has led to landsliding within the study area. In the few cases that do exist this was related to cutting roads through unstable rock or superficial deposits. The construction of the A55 at Pwell Melyn, Holywell in 1976 was delayed due to a landslide, caused by excavation through a relict landslide (Subramaniam and Carr 1983). Extensive remediation work had to be carried out before the road work could continue and the road could be safely used (Subramaniam and Carr 1983). The Rhaullt Hill road cut (Scott 2002) and the A5 trunk road, Glyn Bends (Nichol 2002b) are two locations within the study area where rockfalls were triggered by road construction through unstable rock. The Rhaullt Hill planar wedge failure had to be remediated by a grid of some 650 rock anchors. In addition a drainage system incorporating fifteen 100mm holes was used to reduce the destabilising effect of water on the slope (Scott 2002). . The effect of rainfall on the reactivation of ancient landslides was evident after the intensive rainfall of 2000. This also initiated numerous new slides (Nichol 2002a). Rainfall is the main initiator of recent slope instability in the area particularly those occurring within drift geology.

2.3 Landslide age.

To establish the relative age of landslides within the study area the morphological characteristics of the landslides were assessed based on methods described by Crozier (1986) and Cruden and Varnes (1996) (see Table 2). This is a non-intrusive, practical method that establishes a relative age based on how bare slopes are as a result of the landslide and how distinctive the different landslide features are.

For the landslides where a relative age was determined, 50.5% are recent active (with over half of these are reactivated relict landslides), 27.5% are historically active and 22% are classed as relict (inactive) landslides (see Table 2). It should be noted that there were some landslides that were classified as being recently active in terms of age but not classified as being active in terms of current activity (in the existing digital database). This is due to the situation whereby geomorphic characteristics indicate that there may have been activity in the last 100 years, but they now appear to be stable. Only 46.4% of these landslides are classified as currently being active, based on observed movement in the field.

Analysis of the landslide inventory shows that, approximately 83% of the landslides are in drift geology, 16% are in solid geology, and 1% in both solid and drift geology. Approximately 87% of the landslides that occurred in drift geology were in glacial tills. Smaller percentages were within glacio-fluvial sands, alluvium deposits and head deposits. The smaller landslides within the drift geology are predominantly translational slides and debris/mud flows whereas the larger, less frequent slides are mostly rotational slides. Within the solid geology, rotational landslides dominate, but these are generally inactive. The smaller landslides within the solid geology are invariably active landslides. These are mostly reactivated translational landslides within larger relict rotational landslides, or new active slides within weathered rock. Landslides that occur within solid geology are predominantly within; shale, sequences of argillaceous/arenaceous rocks, sandstone and limestone

Insert Table 2 here

3. Susceptibility modelling

The second stage in the landslide evaluation process was the creation of landslide susceptibility models. Preparation of the landslide susceptibility models involve firstly the identification of landslide controlling parameters (factors) and, secondly the weighting and combination of these factors to create susceptibility models. The landslide occurrence data collected (inventory) was compared with a number of factors believed to contribute to slope instability (see Figure 8). The factors used in this modeling are those observed to be most associated with landsliding, based on mapping/aerial photographic interpretation and previous studies. These include lithology, proximity to fluvial channel, elevation, depth of superficial material, slope angle, slope aspect and proximity to known fault lines. Separate analysis was done for landslides that occurred in solid geology and those that occurred in Drift geology as the controlling factors varied.

Both bivariate (Bonham-Carter *et al.* 1989, Pistocchi *et al.* 2002, Ercanoglu and Gokceoglu 2004, Phi and Bac 2004) and multivariate (Multi Logistic regression) statistical analysis (Süzen 2002, Komac 2006, Yesilnacar and Topal *2005,* Guzzetti *et al*. 2006) were used to determine the importance and significance of factors contributing to slope instability in the study area as well as the classes (e.g. slope gradient of 5-10 degrees). Bivariate statistical analysis was used to: 1) assess the statistical significant relationship between landslide occurrence and the various factors, and 2) assess the density of landslides within each class of factors. Statistical analysis was carried out using SPSS.

*Insert Figure 8 here

The Bivariate statistical analysis shows that in drift geology elevation, proximity to fluvial channel, drift material, slope gradient and superficial thickness are significant at the .01 level (see Table 3) indicating that these factors are significant contributor to slope instability. In solid geology proximity to fluvial channels, proximity to impermeable/permeable boundaries, morphological regions and proximity to fault line are significant at the .01 level (see Table 4) which is strong indicators these factors are significant contributor to slope instability in solid geology.

Insert Tables 3 & 4 here

The density of landslides within each class of factors was calculated. The average landslide density in drift geology is 1.1% and in solid geology 0.48%. Factor classes with density exceeding the average density are deemed as being highly susceptible (Miller 2007). Landslide density analysis of the landslides in drift geology) indicates that some drift materials are more susceptible to slope instability than others. By far the highest percentage of landslides is within glacial till (87%) which covers approximately 70% of the study area (see Table 5). The density of landslides in the till is 1.21%, which exceeds the average landslide density and hence is classified as being highly susceptibility slope. Tills are usually found blanketing slopes within the study area. Clay is one of the main constituents of glacial till, which hinders subsurface drainage and the free movement of water. . In North-East Wales the majority of the steeper slopes, particularly in the upland areas and the banks of fluvial channels, are mantled by tills, glaciofluvial deposits and head deposits. Wherever these are present on moderate to steep slopes there is likely to be a high chance of slope failure occurring, and this may explain the strong relationship with slope gradient and proximity to fluvial channels (see Table 3 and 4).

Insert Table 5 here

The landslide distribution map was overlaid unto the solid geology map and visual inspection indicate a strong association with mudstones (see Figure 8) The is borne out by bivariate analysis. Analysis of the landslides in solid geology indicates that siltstone/mudstone sequences are highly susceptible to slope failure, with approximately 43% of the landslides occurring in these units (see Table 6). Mudstone/shale has the next highest percentage of landslides (20.16%) followed by sequences of shale/sandstone/coal (undivided cyclic), and then sandstone/argillaceous sequences (see Table 6). All of these lithologies have very high landslide densities, indicating that they are highly susceptible to slope instability. What is also notable is that all these lithologies, with a very high landslide density (except for limestone/sandstone sequences), are either mudstones or interbedded with mudstone (argillaceous material). Mudstones/shales are susceptible to slope failure particularly if they are swelling mudstone/shale, or if they are poorly lithified and/or highly weathered and interbedded with permeable layers. Where they are interbedded with permeable layers, for example sandstones, they function as an impermeable layer preventing the free movement of pore water (Miller 2007) This may cause the build up of pore water pressure within the slope. High pore water pressure, which is not released efficiently and quickly, will to lead to an increase in shear stress, which may result in slope failure. The other lithological combination that appears highly susceptible to slope failure based on landslide density is the limestone/sandstone sequences. Of the total study area, only 0.67% is underlain by this material, but wherever it occurs it is highly susceptible to failure. It is likely that this is due to alternating layers of impermeable or semi-permeable and permeable lithologies. For examples, the limestone is extremely hard and dolomitised in some sections (semi-permeable), whereas the sandstone is porous and permeable.

(insert Table 6 here)

Statistical analysis indicates that faulting within the solid geology is a significant contributor to slope instability (see Table 4). Faults may result in planes of weakness within the rock, or act as conduits for ingress of water that may contribute to slope failure. Whilst a fault is represented by a line on geological maps, faulting may have resulted in a fault zone rather than a single sheared surface. The areas of weaknesses created by these faults are more likely to be zones of sheared and brecciated rocks around the defined fault line. Faulting reduces the shear strength of rocks, causing brecciation and/or creating planes of weakness (sheared surfaces, joints). The weakening of these rocks results in them becoming more susceptibility to slope failure (Crozier 1986). The landslide distribution map was compared with the proximity to the fault-line factor map to investigate if there was relationship between the two. Analysis showed that the highest density of landslides is within 10 metres of defined faults, with a gradual reduction in the density of landslides from within 10m to 200metres (see Table 7).

Insert Table 7 here

Insert Figure 9 here

Of all the factors, proximity to fluvial channel is the most significant contributing to the presence of landslides in both solid and drift geology. The highest density of landslides in solid and drift geology occur within 50 metres of fluvial channels (see Tables 8 and 9). Fluvial channels may act both as a conditioning factor and a trigger factor that may lead to slope instability. Fast flowing water within fluvial channels may rapidly cut down through the land surface resulting in rock faces that are generally very steep. Over-steepened (increased slope gradient) land surfaces result in an increase in the shear stress within the rock that increases the probability of failures occurring (Crozier 1986). Fast flowing water may also cause the base of the slope to be eroded, removing the underlying support for the hillside and consequently making it progressively more prone to slope failure. This has major implications for slope instability for this study area due to more intense and varied rainfall predicted due to man-induced rainfall. Such conditions, result in more rapid surface erosion, that create gullying, overstepenning slopes, which will act a slope failure trigger. In addition, rivers which are more frequently in spate will erode the base of slopes which the most significant landslide trigger currently in the study area.

Insert Tables 8 and 9

The bivariate analysis carried out on the landslide data in NE Wales provides a clear indication of the statistical importance of each factor and factor classes to slope instability. It is, however, known that no one factor acts alone, but rather they act in synergy in contributing to slope failure. In order to determine the combination of factors contributing to slope instability in the area and significance of this contributions multivariate statistical regression (multiple logistics) analysis was used. Multivariate analysis was also use to assign the weighting (see Figure 8) to the various factors in order to create the landslide susceptibility model. A fundamental requirement of logistic regression is that multicollinearity should be absent (Menard 1995; Upton and Cook 2002). Multicollinearity is when there two or more independent variables that are strongly correlated. Either one of the variables would be nearly, or as effective on its own than using all of them. As such, if two independent factors show a significant relationship (see Tables 4 and 5) only one is used for further multivariate analysis. To determine which factors are to be eliminated, a Cramer’s V statistical test was used to rank the factors and determine those to be used in the final susceptibility modelling.

3.1 Logistic Regression

In recent landslide evaluation studies Logistic reggresions has being used to create landslide susceptibility map with excellent results (Dai and Lee 2002, Süzen 2002, Ayalew *et al.* 2005, Yesilnacar and Topal *2005,*). Logistic Regression represents a variation of multiple regression modelling and allows one to predict a discrete outcome, such as group membership, from a set of variables (Menard 1995). These variables may be discrete (for example geology), continuous (for example slope angle and elevation), dichotomous (presence or absence of landslide), or a mix of any of the three (Field 2003). The logic or odds are calculated and as the result always falls between 0 and 1, it can be expressed directly as a probability. In logistic regression there is no assumption that the; independent variables should be normally distributed, the dependent and independent variable(s) are linearly related, or that there must be equal variance within each group. The major assumption is that multicollinearity is absent (Field 2003). The relationship between the predictor and response variables is not a linear function in logistic regression. Instead, the logistic regression function uses a logit transformation of P(*y*) and may be expressed as:

$$P(y) = \frac{e^{(\alpha+\beta 1X1+\beta 2X2+...+\beta nXn)}}{1+e^{-(\alpha+\beta 1X1+\beta 2X2+...+\beta nXn)}} \qquad (1.1)$$

Where P(y) is the probability of an event occurring, α is the constant of the equation and β = the coefficient of the predictor variables (x).

Where there is more than one predictor (independent) variable, the relationship between the dependent variable and the predictor is expressed in a simpler format that can be applied to landslide assessment using the equation:

$P(y) = 1/1+e^{-Z}$. (1.2)
$Z= \beta^0+ \beta_1X_1+ \beta_2X_2+\ldots+ \beta_nX_n+ \varepsilon_i$

Where $P(y)$ is the probability of a landslide event occurring, β^0 is the constant, $\beta_1, \beta_2 \ldots \beta_n$ are the coefficients calculated for the independent variables and $X_1, X_2\ldots X_n$ are the values of the independent variables, and ε_i is the residual term (Field, 2003). The probability of the event not occurring is equal to
1- P(*y*).
The coefficients values calculated were used as weights for each independent factor in the creation of the susceptibility or hazard models. As the mode and distribution of landslides in drift geology differed from those in solid geology, the landslides were separated into the two categories and separate analysis carried out. The landslide database was also (randomly) divided into two datasets - one for use in creating the susceptibility models, and the other for validation of the models. A backward stepwise regression (Menard 1995) was then used to determine the combination of factors which best determined the presence/absence of landslides in drift geology and solid geology. The key hazard controlling parameters determined by the logistic regression are: geology, proximity to known structural weaknesses, slope angle and proximity to fluvial channels.

3.2 Susceptibility modelling using logistic regression

The coefficients calculated from the regression analysis were used as the weightings for each factor. These coefficient values were then inputted into equation 1 to create the final susceptibility map. As categorical data were used, equation 1 was modified to calculate '**Z**' for the landslides in drift geology (eqn. 3, below) and solid geology (eqn.4, below). The modified equations are as follows:

$$Z= \beta^0+ \beta_1 (\text{weighted Distance from fluvial channel classes}) + \beta_2 (\text{weighted slope angle classes}) + \Sigma(\beta_K \text{ Superficial type}_K) \qquad (1.3)$$

where $\beta^0 = 6.504$, $\beta_1 = 0.711$, $\beta_2 = 0.637$ *and*
$\Sigma\ \beta_K$ *Superficial type*$_K$*)= (-10.692 * Peat class) + (-2.484*Glaciofluvial class) +(-0.3068 * Head deposit) + (0.505 Till class) + (-10.441*Tufa) + (0* 'all other classes').*
β_K *= coefficient of the individual superficial material type, Superficial type* $_{K=}$ *weighted individual superficial material classes*

$$Z= \beta^0+ \beta_1 (\text{Distance from fault lines classes})+ \Sigma(\beta_m \text{ Lithology}_m)+ \beta_2 (\text{weighted Distance from fluvial channel classes}) \qquad (1.4)$$

where $\beta^0 = -0.012$, $\beta_1 =-0.4310$, $\beta_2 = -0.0604$, *and*

*$\Sigma(\beta_m \text{ Lithology}_m)$ = (0.163*Siltstone/Mudstone class) + (0.245*Mudstone class) + (0.131*Sandstone/argillaceous class) + (-0.235*Limestone/sandstone class) + (0.241* Limestone/argillaceous class) + (0.011*Sandstone class)+ (0.110 *Volcanics/volcaniclastics class) + (-0.112* Siltstone class) + (-0.316*Tuff class) + (-0.316*Undivided cyclic sediments class) + (-1.313*Halite class + (-1.101 * Breccia/conglomerate class) + (-0.017*Poorly lithified sand/silt/clay class) + (-2086*others class)*
Where β_m = coefficient of the individual lithology classes, $\text{Lithology}_{m =}$ weighted individual lithology class)

4. THE LANDSLIDE SUSCEPTIBILITY MODELS

The landslide susceptibility models were created in the GIS through combination of the relevant weighted factor maps. This combination was dictated by logistic regression rules and based on equations 1.3 & 1.4. Only the factors indicated by the logistic regression model as being the most useful in creating the susceptibility model were used in the GIS. The classes within each factor (variable) were firstly reclassified - this was achieved by assigning the density calculation value for each class as its new value. The map created is a weighted factor class map. Each weighted factor class map was subsequently multiplied by the coefficient factor calculated by the logistic regression analysis using the Raster Calculator™ in ArcGIS™. The Raster Calculator was then used to combine the weighted layers in the manner stipulated in equations 1.3 and 1.4 to produce raster-based maps with probability values assigned to each cell. These maps were divided into susceptibility zones based on the probability values calculated to create susceptibility maps for the study area (see Figures 10 and 11).

4.1 Landslides in drift geology model

In total approximately 8% of the study area is classified as high or very high susceptibility compared to 27% as moderate, and 63% as low susceptibility. Visual inspection of the models (see Figure 10) highlight the strong influence of fluvial channels on the model. This is not surprising as fluvial channels demonstrated the strongest association with slope instability in the logistic regression analysis (see β value from eqn 1.3 & 1.4) and the test of strength of relationships. Generally the high and very high susceptibility zones coincide with areas of erosion along fluvial channels within tills and alluvium that are located on moderate sloped land. The areas of low landslide susceptibility coincide mainly with low lying areas with low slope angle ($<5^0$) or high slope angles ($>25^0$) away from drainage channels. Land surfaces within the Vale of Clywyd, the Cheshire Plain and the upland areas of Hope Mountain are typically areas designated as being low susceptibility (see Figure 10). Although the superficial geology is thickest in the lowland areas, the other factors contributing to slope failure are not as frequently present. In the highland areas with very steep slopes, drift cover has frequently been removed/divided by surface water erosion and hence landslides in drift geology are unlikely to occur here. This might be the reason why these areas have been classified as low susceptibility.

In areas such as, the Denbigh Plateau, Holywell, Llangollen and the banks of the upper reaches of the River Dee, the slopes are typically of moderate angles blanketed by glacial deposits, with a high degree of erosive drainage channels. Generally these are the areas that the model indicates are highly susceptible to slope instability. Based on visual inspection of Figure 10 highlights areas that are in good accordance with the overall distribution of landslides on the inventory map. It accurately demarcates areas of landslide cluster on the inventory map, but also identifies other areas as being highly susceptible which have no record of failure to date for example, the scattered the area south of Colwyn Bay north and west of Berwyn. Recently there has been a failure within Berwyn area (GR: 3007,3315) that is impacting on the road. This provides one indication of the usefulness of the model in highlighting areas (with no record of landsliding to date) that may be prone to instability in the future.

Insert Figure 10 here

4.2 Landslides in solid geology model

The landslide susceptibility models created for landslides in solid geology (see Figure 11) indicated that approximately 12% of the area is classified as high and very high susceptibility compared to 56% as moderate, and 32% as low susceptibility. The influence of drainage channels is also evident in this model but not as pronounced as in that for the drift geology. The influence of proximity to fluvial channels, lithology and fault-lines are evident in this model. The areas corresponding to high susceptibility coincide with lithologies prone to failure (e.g. shale and sandstone/argillaceous sequences), and where there is a high density of known fault-lines. The combination of these factors are most evident in the north-east of the study area, such as on the flank of Halkyn Mountain and the North Wales coalfield area. The areas classified as low susceptibility are mostly in areas with a low density of river channels and underlain by lithologies (e.g. volcaniclastics, homogenous limestone, sandstone and siltstone) that are not interbedded with argillaceous material (see Figures 9 &11). At a regional scale (refer to Figure 11), sections of the Vale of Clywyd and Bettws Gwefil are two such areas. In general, susceptibility is highest in areas underlain by rocks of Carboniferous age and lowest in those areas where rocks of Ordovician and Triassic age are present. The areas underlain by rocks of Silurian age (mudstones/sandstones), for example in the Denbigh Plateau are susceptible to slope failure but less so than areas underlain by Carboniferous sequences (thick layers of dolomitise limestones).

In general, there is good accordance between the susceptibility model and the overall distribution of landslides on the inventory map. Like the model for slides within drift geology it accurately demarcates areas of landslide cluster on the inventory map, but also indicates zones in other areas as being highly susceptible that have no record of failure to date. One such place is the area south of Dolwen (2909,3751) and Rhostyllen just west of Wrexham (3323,3482).

Insert Figure 11 here

5. Intended use and limitation of the models

The susceptibility models created are intended for use as a general guide to depicting areas of relative susceptibility to slope failure and as a predictor of landslide hazard at specific sites. Areas of high and very high landslide susceptibility depict the potential for slope failure to occur but do not depict: the time frame of the failure, the type of failure, the volume of the material likely to be generated nor the path of any debris (Ahmad and McCalpin 1999). The models have been created at a regional scale and cannot be used as a substitute for site-specific work, and/or in place of professional advice from qualified geologists, geotechnical engineers and planners before development takes place. An explanation of each zone is provided below.

Low susceptibility zones

Areas assigned to this category can be considered least susceptible to slope instability. These are areas where the combination of factors contributing to slope instability are generally absent. These areas should remain stable unless there is extensive disturbance from human activity or significant change in environmental/climatic conditions. A low level of geotechnical investigation is normally required for these sites as far as slope instability is concerned.. Although there is a low probability of landslides all site development should be guided by stipulated planning and other building regulations (Ahmad 1999).

Moderate susceptibility zone

The combination of factors contributing to slope instability is unlikely to result in landslides unless the existing ground conditions are radically altered, for example as a consequence of deep excavation during large site development. Changing land-use and human disturbance may change these slopes from being marginally stable to unstable. Changes in climatic/environmental conditions such as rising sea level and increases in rainfall intensity and duration may initiate landslides in these areas. Low to moderate geotechnical investigation may be required, depending on the scale and nature of proposed development.

High and Very High susceptibility zones

Within these areas the combination of factors contributing most to slope instability is normally present. Landslides are likely to occur within these areas as a result of human disturbance and/or current environmental/climatic conditions. Minor changes in ground-water conditions (pore water pressure), increased surface run-off, slope undercutting and increases in slope angle may all result in slope failure. A high level of geotechnical investigations is required for these areas.. Slopes may have to be stabilized before development can safely take place. Stabilisation may be achieved through engineering structures such as soil nailing, gabion baskets, rip rapped surfaces and retaining walls, along with engineered drainage systems. Development within the areas assigned as being of very high susceptibility should be avoided at all cost unless there are no alternative areas available.

The susceptibility maps may be used as tools to help reduce the loss associated with slope instability from both existing and future landslides. Using these maps as guidance, citizens, planners, engineers and developers may reduce loss due to slope instability through prevention, mitigation and/or avoidance of areas prone to slope instability. In summary these maps may be used as a tool for;

1. Monitoring and regulating new development in hazardous areas guided by planning controls (Ahmad and McCalpin 1999).
2. Identification of areas where landslide mitigation is needed. In such areas, mechanisms to reduce the impact of slope instability, for example by means of engineering structures, planning and land-use control, may be implemented.
3. Discussion and adoption of appropriate strategies for dealing with landslides and/or potential landslides.
4. Public awareness and education.

6. Validation

Landslide susceptibility maps once created need to be validated to establish their; reliability, robustness, degree of fit and predictive capability (Guzetti *et al*. 2006). As indicated by Chung and Fabbri (2003), without validation of the prediction modeling, a model is of little use and hardly has any scientific significance. One subset of the landslides mapped were used to construct the model (training set) and the second subset set aside to test the model (Chi *et al*. 2002).

The model was tested firstly using the second subset distribution of existing landslides. Approximately 80% of the existing landslides fall within the high and very high susceptibility zones (see Table 10). Half (49.8%) of the landslides fall within the very high susceptibility zone, even though this represents a mere 2% of the total study area. Conversely, nearly 52% of the area was designated ‘low’ susceptibility and this accounted for just 5% of the landslides. This prediction rate compares favourably with previous studies (Dai and Lee 2002, Süzen 2002, Yesilnacar and Ayalew *et al.* 2005, Topal *2005*).

In the second test, using future landslides’ (recent landslides not used in the modeling) the model succeeded in placing 50% of the landslides within the very high susceptibility zone and the other 50% within the high susceptibility zone. Although there are too few slides to statistically test if this was just by chance, it might be justifiable to say the model has some potential to predict the location of ‘future’ landslides in the area.

Insert Table 10 here

Conclusion

Landslide occurrence in North-East Wales is more common than previously thought (pre 2002), with an updated record of 430 landslides (compared to 244 in earlier studies). The new GIS database for the area indicates that landslides occur more commonly in drift material than in solid geology. Relict landslides are the most dominant landslides, however, reactivation of existing landslides is common. In addition, there are recent active landslides occurring in areas of previously stable land that have not been previously mapped. It is suggested that due to changing land-use, climatic, environmental and geomorphological factors, land that was previously stable or marginally stable has now become unstable. By using GIS to identify factors contributing to slope instability in solid and drift geologies landslide susceptibility models have been created that are capable of identifying areas (without existing landslides) that have a high propensity for new slope failure.

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Table 1 Percentage of landslides in landslide database classified by type

Landslide type	Percent
Complex	1.0
Falls	3.1
Flows	3.1
Rotational Multiple	4.1
Rotational Single	42.8
Translational Single	45.9
Total	100.0

Table 2. Determining the relative age/activity of landslides (Modified from Cruden and Varnes, 1996).

Age	Definition
Recent/ Active	Slope currently moving, site displaying cyclical pattern, with a periodicity of up to 5 years. First time failure and/or reactivated failure observed within the last 100 years. Sharp geomorphologic expression of landslide features is still distinctive, with clearly defined scarp, body and toe. The slide is mostly bare, with little or no vegetation present on it.
Historically active	Mass movement on a slope within historic timescale (100-1000 years). No evidence of current movement. Relative youthful geomorphic expression of the slides still exists. The scarps may still be clearly evident and bare, but the debris on body of the landslide may be absent or modified and secondary vegetation present. Where mature trees are present their trunks may be curved as evidence of very slow slope movement over a number of years.
Relict	Mass movement which occurred within early historic and prehistoric times and which is associated with a different environmental condition than exists today, e.g. periglacial. The morphological impression of landslides may still be observed, but it is more mature and subdued. Scarps have become rounded and less steep due to erosion and can be classified as being stable. There is no indication of contemporary movement. Slopes may be completely re-vegetated by natural forest.

Table 3 Bivariate statistical analysis of factors contributing to slope instability (drift geology) (output from SPSS)

	Variables 2							
	Presence/ Absence of landslide	Elevation	Proximity to fluvial channels	Drift material	Slope angle	Slope aspect	Underlying solid geology	Superficial thickness
Presence/ Absence of landslide	1.000 . 356	-.166** .001 356	.458** .000 356	.159** .002 356	.189** .000 356	.095* .038 356	-.105 .036 356	.296** .000 356
Elevation	-.166** .001 356	1.000 . 356	.166** .000 356	.130** .006 356	.002 .962 356	.081 .054 356	-.117* .011 356	-.332* .000 356
Proximity to fluvial channels	-.458** .000 356	.166** .000 356	1.000 . 356	.057 .213 356	-.108* .012 356	.038 .346 356	.154** .000 356	-.169* .000 356
Drift material	.159** .002 356	.130** .006 356	.057 .213 35	1.000 . 356	.104 .029 356	.077 .082 356	-085 .082 356	-.148* .003 356
Slope angle	.189** .000 356	.002 .962 356	-.108* ..012 356	.104* .029 356	1.000 . 356	.099* .019 356	.098* .034 356	.119* .012 356
Slope aspect	.095* .038 356	.081 .054 356	-.038 .346 356	.077 .082 356	.099* 0.19 356	1.000 . 356	-.061 .157 356	-.015 .743 356
Underlying solid geology	-.105* .036 356	-.117* .011 356	.154** .000 356	-.085 .082 356	-.098* .034 356	-.061 .157 356	1.000 . 356	.208* .000 356
Superficial thickness	.296** .000 356	-.332** .000 356	-.169** .000 356	-.148** .003 356	-.119* .012 356	-.015 .743 356	.208** .000 356	1.000 . 356

Table 4 Bivariate statistical analysis of factors contributing to slope instability (solid geology) (output from SPSS)

	Presence/ Absence of landslide	Elevation	Lithology	Formation	Proximity to fluvial channels	Slope angle	Slope aspect	Proximity to impermeable boundaries	Morphological regions	Proximity to fault lines
Presence/ Absence of landslide	1.000 . 141	-.047 .539 141	.178* 022 141	.078 .293 140	-.506** .000 141	.136 .075 141	.018 .805 141	-.355** .000 141	-.295 .002 141	-.295** .000 114
Elevation	-.047 .539 141	1.000 . 141	-.076 .279 141	.-.130 .053 140	.206** .003 141	.163* .018 141	.021 .754 141	.034 .642 141	-.136* .047 141	-.019 .801 114
Lithology	.178* .022 141	-.076 .279 141	1.000 . 141	.-.003 .966 140	.062 .381 141	-.154* .028 141	.005 .942 141	.101 .181 141	.210** .003 141	-.014 .819 114
Formation	.078 .293 140	-.130 .053 140	-.003 .966 140	1.000 . 140	-.106 .199 140	-.037 .583 140	-.064 .324 140	-.134 .064 140	.257** .000 140	-.046 .525 113
Proximity to fluvial channels	.506** .000 141	.206** .003 141	.062 .381 141	-.106 .119 140	1.000 . 141	-.072 .303 141	.048 .476 141	.175* .019 141	-.044 .526 141	.056 .454 114
Slope angle	.136 .075 141	.063* .018 141	-.154* .028 141	-.037 .583 140	-.072 .303 141	1.000 . 141	.083 .211 141	-.141 .058 141	-.178** .010 141	-.059 .432 114
Slope aspect	.018 .805 141	.021 .754 141	.005 .942 141	-.064 .324 140	.048 .476 141	.083 .211 141	1.000 . 141	.180* .012 141	-.131* .047 141	.011 .880 114
Proximity to impermeable boundaries	-.355** .000 141	.034 .642 141	.101 .181 141	-.134 .064 140	.175* .019 141	-.141 .058 141	.180* .012 141	1.000 . 141	-.383** .000 141	.273** .001 114
Morphological regions	-.236** .002 141	-.136* .047 141	.210** .003 141	.257** .000 140	-.044 .526 141	-.178** .010 141	-.131* .047 141	-.383 .000 141	1.000 . 141	-.156* .038 114
Proximity to fault lines	-.295 .000 114	-.019 .801 114	-.017 .819 114	-.046 .525 113	.056 .454 114	-.059 .432 114	.011 .880 114	.273** .001 114	-.156* .038 114	1.000 . 141

						114	114			

Table 5. Density and percentage of landslides within classes of drift geology

Superficial material	**% of slides in class**	**% of total area**	**Density of landslides in class**
Alluvium	3.48%	9.63%	0.36%
Storm beach	0.17%	0.21%	0.77%
Blown sand	0.02%	0.54%	0.04%
Glaciofluvial	8.88%	11.24%	0.78%
Head	1.12%	1.01%	1.10%
Lacustrine	0.07%	0.80%	0.09%
Peat	0.06%	2.88%	0.02%
River terraces	0.17%	2.58%	0.06%
Undifferentiated	0.37%	0.69%	0.54%
Talus	0.00%	0.01%	0.00%
Till	85.67%	70.36%	1.21%
Tufa	0.00%	0.04%	0.00%

Table 6. Density and percentage of landslides within classes of lithology (solid geology)

Lithology	Percentage of slides	Percentage of class	Landslide density
siltstone/mudstone	42.85%	36.85%	0.48%
siltstone	0.00%	1.14%	0.00%
tuff	0.00%	0.14%	0.00%
mudstone	20.16%	12.23%	0.69%
sandstone/argillaceous	13.68%	11.30%	0.50%
limestone/sandstone	1.98%	0.67%	1.23%
volcaniclastics	0.00%	0.00%	0.00%
limestone/argillaceous	1.55%	1.47%	0.44%
shale/sandstone/coal (undivided cyclic sequences)	14.75%	12.56%	0.49%
halite	1.28%	1.07%	0.00%
limestone	1.28%	6.32%	0.08%
sandstone	3.75%	1.51%	0.11%
others	0.00%	0.11%	0.00%

Table 7. Density and percentage of landslides within classes of distance from fault-lines (finer divisions at lower end of the scale where impact may be greatest and which need to be distinguished).

Distance (m)	Percentage of slides	Percentage of class	Landslide density
0-10	15.76%	6.14%	0.55%
11-50	13.88%	7.48%	0.39%
51-100	9.30%	5.76%	0.34%
101-200	12.43%	8.43%	0.31%
201-300	10.76%	5.65%	0.40%
301-400	5.28%	3.77%	0.30%
401-500	1.70%	3.11%	0.12%
>500	30.89%	59.67%	0.11%

Table 8 Density and percentage of landslides within classes of proximity to fluvial channel (drift geology) (Finer divisions at lower end of the scale where the effect might be greatest)

Proximity to fluvial channel (m)	Percentage of slides in class	Percentage of total area	Density of landslide within class
0-50	32.75%	6.47%	3.40%
51-100	15.50%	3.52%	2.96%
101-150	14.45%	3.94%	2.46%
151-200	8.83%	3.25%	1.82%
201-250	8.31%	3.86%	1.44%
251-300	4.70%	2.80%	1.12%
301-350	3.75%	2.59%	0.97%
351-400	5.46%	2.79%	1.31%
>400	6.26%	70.77%	0.06%

Table 9. Density and percentage of landslides within classes of proximity to fluvial channel (solid geology). (Finer divisions at lower end of the scale where impact may be greatest and which need to be distinguished).

Proximity to fluvial channel (m)	**Percentage of slides**	**Percentage of class**	**Density of landslide within class**
0-50	33.41%	7.18%	1.10%
51-100	14.38%	4.89%	0.87%
101-150	12.91%	5.48%	0.69%
151-200	9.21%	4.52%	0.60%
201-250	8.88%	3.84%	0.49%
251-300	4.96%	2.78%	0.38%
301-350	3.52%	2.57%	0.29%
351-400	2.62%	2.77%	0.20%
>400	10.10%	70.23%	0.03

Table 10 Results of predictive capability of susceptibility model (drift geology)

Susceptibility zone	**Susceptibility zone (Percentage of total area)**	**Percentage of slides (slides not used in model creation)**	**Percentage of recent ('future') landslides**
Very high	2	49.8	50
High	6	30.0	50
Medium	27	14.8	0
Low	52	5.4	0
None	13	0	0

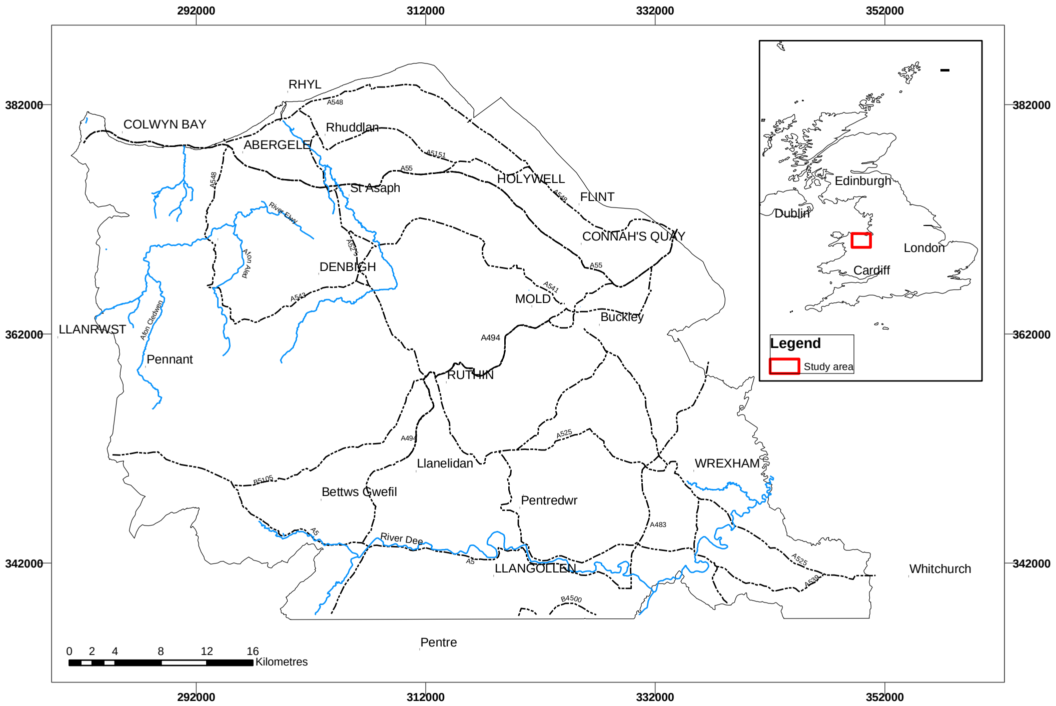
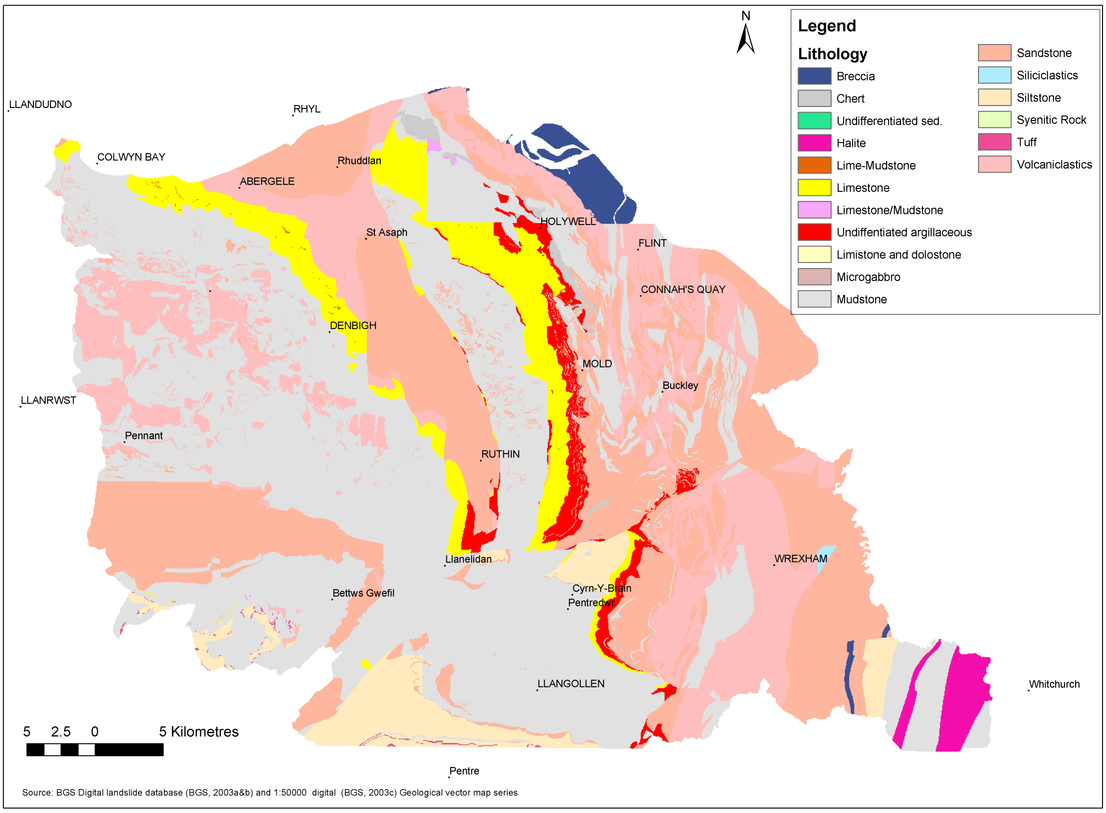


Figure 1 Location of the study area



Source: BGS Digital landslide database (BGS, 2003a&b) and 1:50000 digital (BGS, 2003c) Geological vector map series

Figure 2 Lithological (solid Geology) map of the study area

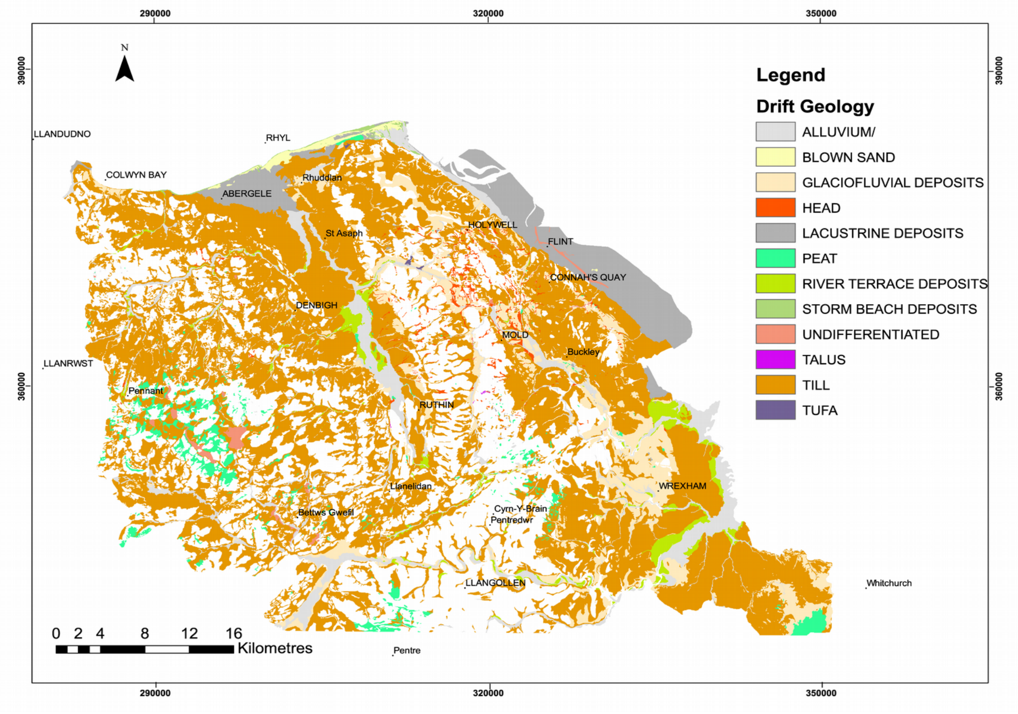


Figure 3 Drift geology of the study area (modified from BGS, 2003a)

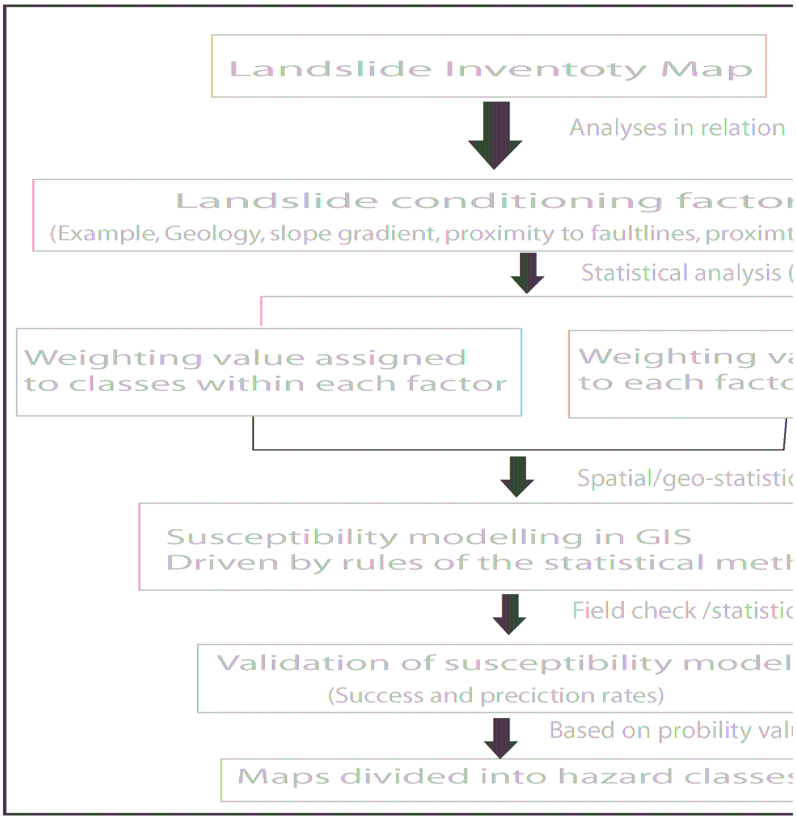
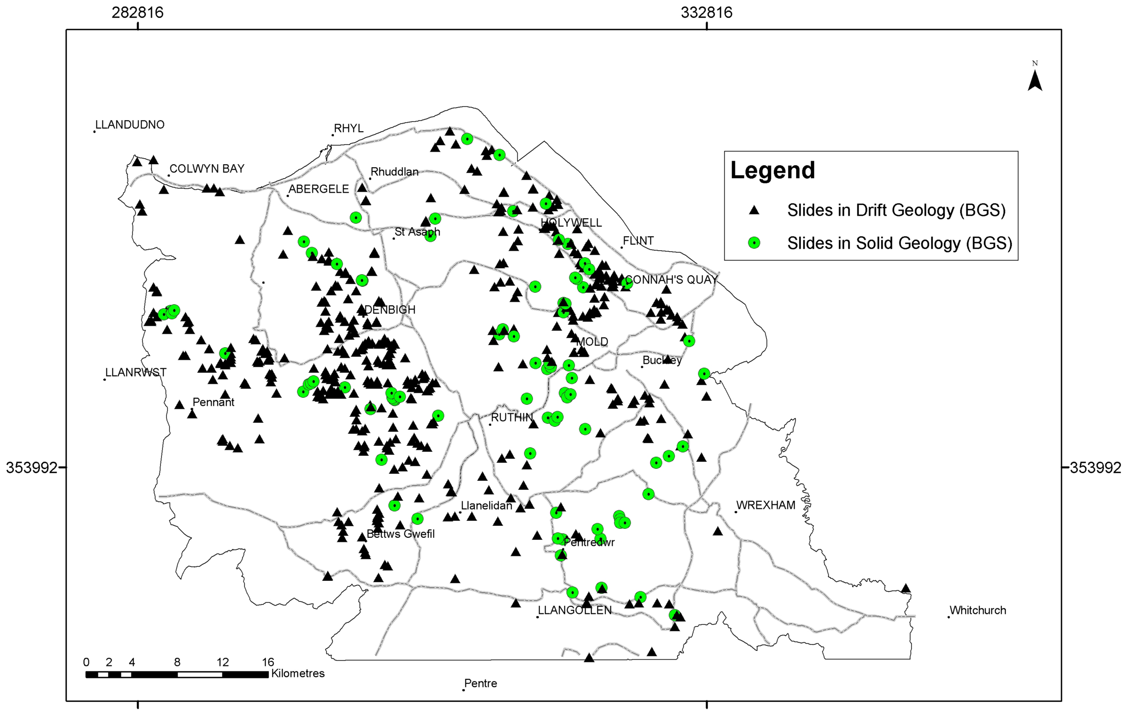


Figure 4 Stages in landslide hazard assessment.



NB. Each point represents a single landslide regardless of size.

Figure 5 Landslide inventory for the North-East Wales (solid and drift geology)

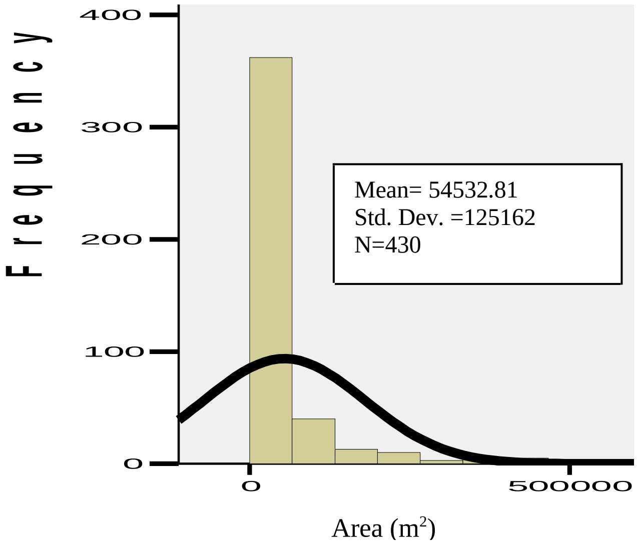


Figure 6 Frequency histogram plot of landslide area for the study area.

Figure 7 Photograph looking towards the slip surface of a translational slide in glacial till at Eglwyseg Mountain, NE Wales (GR:324429,343018).

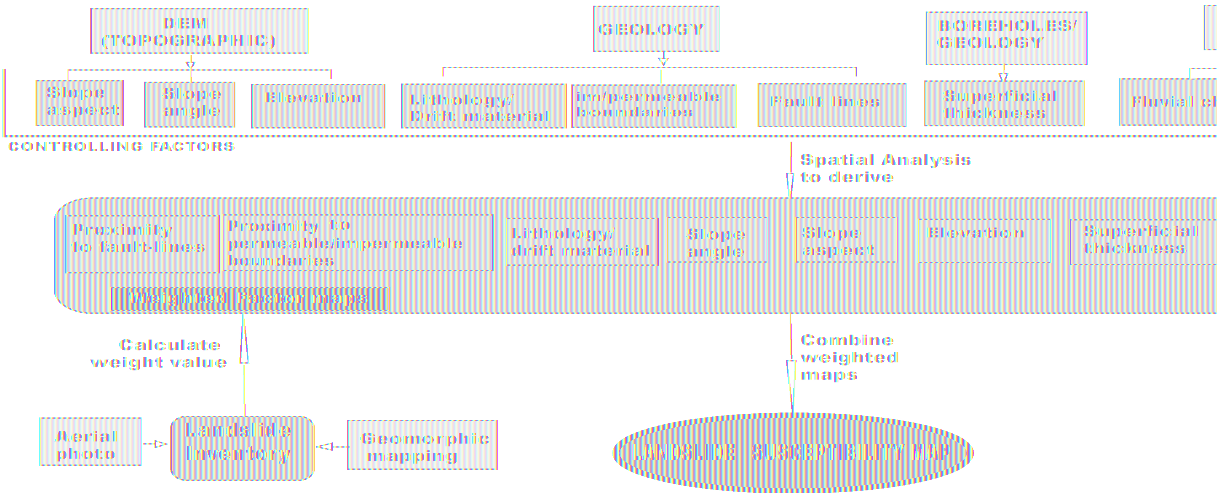
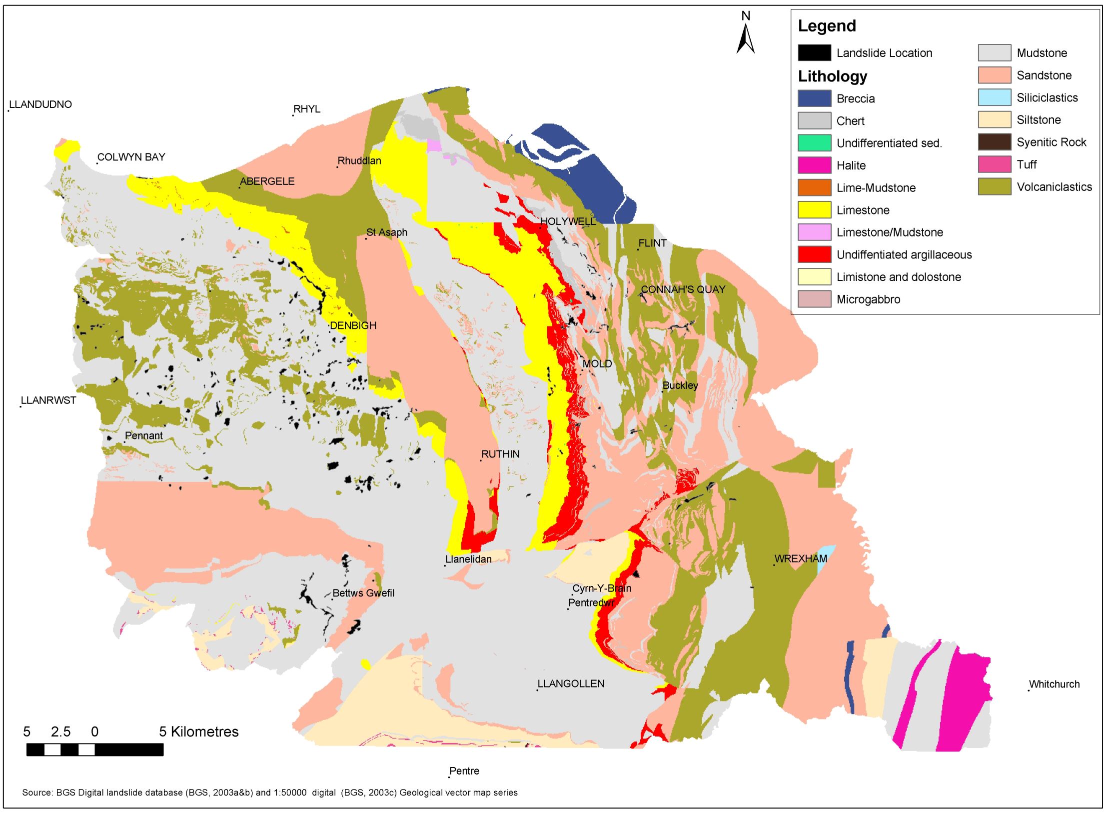


Figure 8. Graphical illustration of the stages involved in the creation of the landslide susceptibility map



Source: BGS Digital landslide database (BGS, 2003a&b) and 1:50000 digital (BGS, 2003c) Geological vector map series

Figure 9 Landslide distribution and lithological (solid geology) factor map

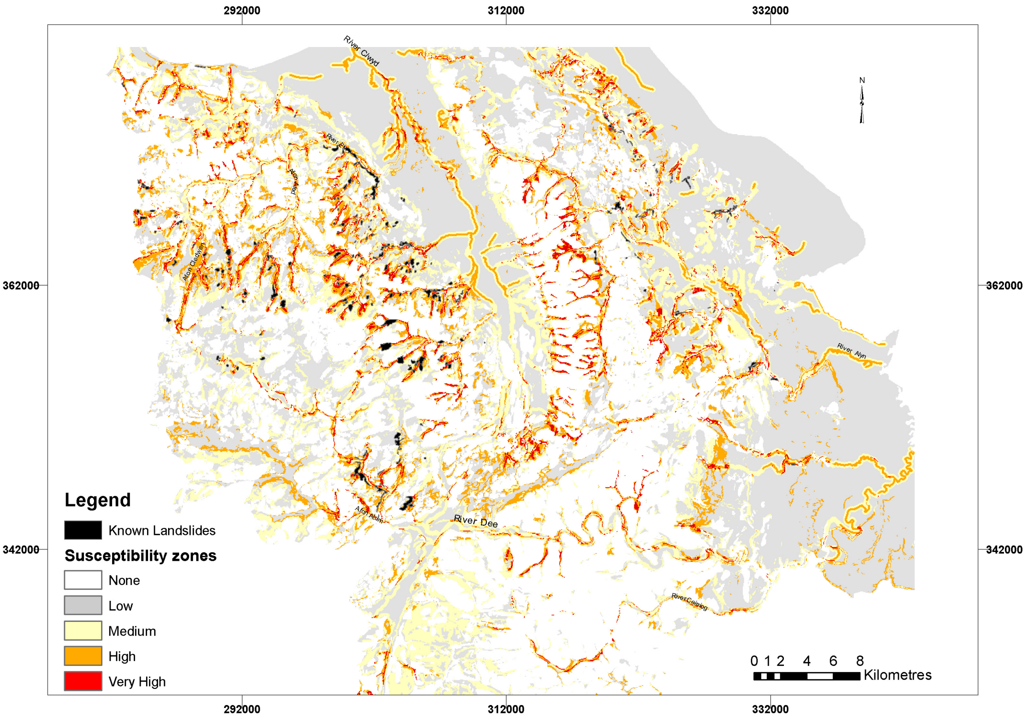


Figure 10. Landslide susceptibility Model (landslides in Drift geology)

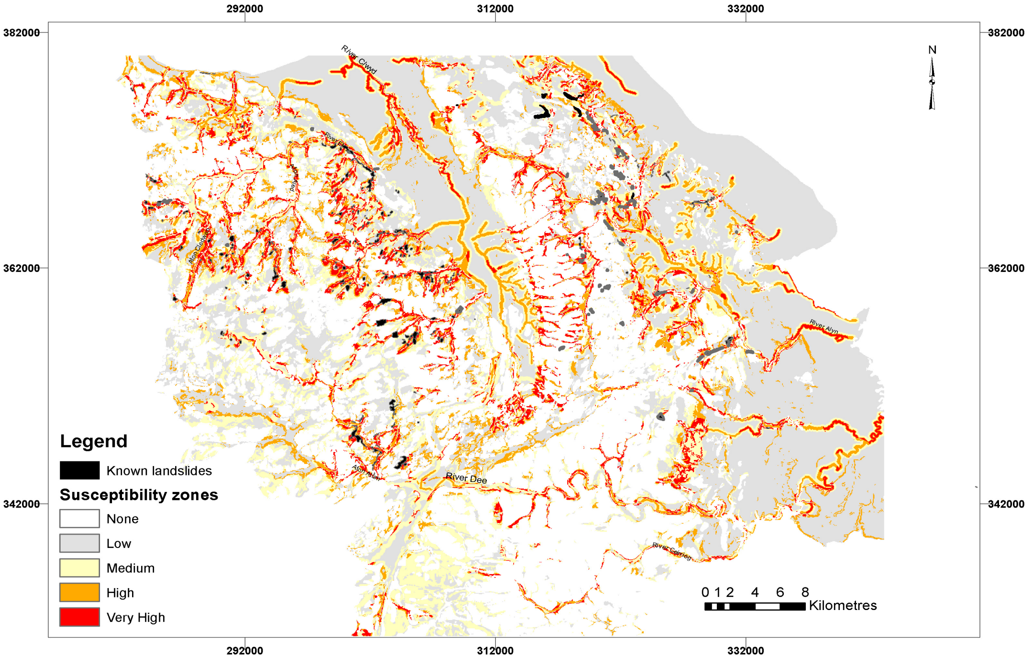


Figure 11. Landslide susceptibility Model (landslides in Solid geology)