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Landslide hazard mapping: Slovakia case study

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Front cover illustration: Landsliding in the Javorniky Mountains

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EXECUTIVE SUMMARY

The British Geological Survey has undertaken a programme of research on landslide hazard mapping under support from the Department for International Development. The aim of these studies has been to develop a generic approach to landslide hazard modelling that can be applied and adapted in developing countries worldwide. The overall goal of the research is to prevent or minimise the loss of life and damage to property, infrastructure and livelihoods caused by landslides. To this end, case studies in four countries have been used to develop a rapid, inexpensive method for the production of regional landslide hazard maps. This report presents specific results and findings from the Slovakian study area in the Javorniky Mountains.

Conventional landslide hazard mapping involves expensive, time-consuming ground surveys and sub-surface investigations. It is essential for site-specific studies that support new infrastructure development, but cannot be justified for wider regions. This report describes an alternative approach that does not provide site-specific information but instead depicts broad zones of hazard for a whole region. The resulting hazard maps do not show the actual hazard for any particular location, but they can be used as a guide to planning and to help select sites for detailed follow-up studies. The method is based on the principle that the past is the key to the future. It uses a landslide inventory for the study area that shows where landslides have already occurred. This is compared to a range of possible controlling factors, depicted in a series of thematic maps. The degree of control exerted by each factor, such as geology or elevation, is evaluated. The thematic maps are then reclassified in terms of landslide susceptibility before being combined to produce the final hazard map.

The method achieves savings in time and costs through the use of remote sensing and Geographic Information Systems (GIS). The landslide inventory is created through the interpretation of aerial photographs or satellite images, with a minimum of necessary field checking. The manipulation of the thematic map data and its statistical analysis is carried out in a GIS. Developments in computing and Earth observation systems mean that these methods can now be used on inexpensive personal computers that are affordable in development projects. In Slovakia, the small scale of the landslides that occur means that aerial photography is the best data type to use in the production of the landslide inventory. Satellite data with sufficient resolution are now becoming available, such as those from the Ikonos satellite, but this was not the case during the main phase of this study. The most important controlling factors on landslide occurrence are the geology, depth and type of weathered material, slope steepness, shallow groundwater table and faulting. Most landslides are shallow debris slides involving weathered bedrock material and occur over particular lithologies. It is therefore probable that these formations possess lithological characteristics that promote deep weathering and make them vulnerable to landsliding when triggering events such as heavy storms or intense melting of snow cover occur, particularly in areas with steeper slopes.

This report is aimed at people and organisations in Slovakia that are concerned with or affected by landslides. It discusses local issues that affect the development of landslide hazard preparedness strategies in individual countries. The accompanying map is a first attempt at mapping the regional landslide hazard in this part of Slovakia. It can be improved through additional local knowledge and the incorporation of more data on possible controlling factors, for example. Ultimately, the success of the project can only be judged by the take up, use and development of the hazard map in Slovakia.

CONTENTS

1 INTRODUCTION

1.1 Background

This report is one of four resulting from a research project on landslide hazard modelling undertaken by the British Geological Survey (BGS) with support from the Department for International Development (DFID). It describes work undertaken in Slovakia in order to develop a methodology for mapping landslide hazards rapidly and cost effectively over wide areas. Parallel development work on a contrasting style of landslide in Jamaica is described in a separate report (Northmore *et al.*, 2000). The resulting strategy for landslide hazard preparedness is set out in Greenbaum *et al.* (2000) and summarised in Marsh (2000).

Landslides are a common natural hazard throughout much of the developing and developed world. They occur when extreme events such as heavy rainfall or earthquakes trigger mass movement of ground that is only marginally stable. On a human time scale, landslides occur infrequently and tend to be regarded as unusual occurrences. However, from a geological perspective they are nothing exceptional and probably form the main erosional process in many regions. It is possible to examine their distribution in space and time in comparison to a range of triggering factors and potentially unstable surface materials. Statistics can be used to predict the likelihood of such events occurring in the future in a particular location. This is the rationale behind landslide hazard modelling.

In conventional landslide hazard modelling, expensive and time-consuming ground surveys and sub-surface investigations are used at the local level to produce detailed, site-specific maps for use in planning. These are essential where major new infrastructure or other developments are planned in a region prone to landslides. However, the approach is too expensive and slow to be used over wide areas. This research project has developed an alternative approach aimed at producing regional landslide hazard maps quickly and at low cost. It uses information that is either readily available for many countries, or can be easily obtained. The approach is based on the principle that the past is the key to the future; landslides are most likely to happen in areas where the conditions that caused past landslides pertain today. Remote sensing is used with limited field surveying to map existing landslides. Their distribution is then compared to that of a range of ground conditions and triggering mechanisms to understand why they occurred where they did. Finally, this understanding is used to classify a map of these same factors over a wider area in terms of landslide hazard.

The resulting maps may not be as reliable as those produced by conventional ground surveys but they do at least provide a preliminary indication of hazard over a whole region. They can be used for general planning purposes, and to guide the siting of more detailed, local ground investigations. This report details the application of the hazard modelling approach to the landslides in the Slovakian study area, the Javorniky Mountains. It gives the regional setting, describes the type of landslides that occur, sets out the remote sensing methodology used to map them and the GIS methodology used to model the hazard. The resulting hazard map is also presented.

1.2 The Impact of Landslides in Slovakia

In Slovakia, whilst lives are rarely lost because of landslides they have an impact on both urban and rural infrastructure; up to 550 villages and towns are endangered as a result of their location at or near areas of old landslides. A well-known example is the case of Handlova town in Central Slovakia, where landsliding destroyed an essential part of the town in 1960. Destabilised ground poses a threat to rail and road infrastructure at numerous sites. Unstable ground also makes much of the land area unsuitable for commercial agriculture. Most old, stabilised ground that has in the past been affected by landslides is now devoted to meadows, pastures, gardens or forestry. As a means of quantifying the scale and extent of landsliding in the different regions of Slovakia, a series of engineering geological maps were produced classifying areas in terms of different types of slope stability (Malgot and Baliak, 1993). The reader is referred to these maps for more information on landslide impacts in Slovakia.

1.3 Landslide Hazard Maps

As in many other parts of the world, landslides constitute a common and an important erosional process that shapes Slovakia's landscape. Science and technology are some way from allowing us to forecast when and specifically where, a particular landslide will occur. However, we do have a sound understanding of the factors that control the general development of landslides. These include the underlying geology and lithology, slope steepness, and rainfall severity. If those causal factors can be identified, recorded, measured and mapped, analysis of their distribution allows the identification of areas with varying potential for, or susceptibility to, future landsliding. Using appropriate analytical techniques, this knowledge can be used to identify broad zones in any given terrain that are most susceptible to slope movement. The importance of specific factors in a particular region can be judged by assessing the regional occurrence and distribution of existing landslides, which must reflect the occurrence of the combination of factors that resulted in the original slope failures. This, then, is the logic behind regional landslide hazard assessment and the preparation of regional hazard maps; map the existing landslides, determine the factors that caused them, map those factors across the region and so assess the regional hazard. Thus, landslide hazard maps display the extent of potentially threatening landslide events across a region by showing divisions or zones reflecting the scale or intensity of the landslide hazard (hazard zonation). This zonation is based on statistical analysis of the acquired, spatially distributed base-line data (the landslide inventory and identified controlling factors). These maps are also referred to as landslide potential or susceptibility maps.

A variety of hazard assessment techniques exist that should prove suitable for a wide range of situations, depending on the extent of the area under consideration, the type of landsliding and available base-line data. In the present study, and of particular relevance to developing countries, methodologies for the rapid assessment of landslide hazards have been developed. These are suited to a variety of terrain conditions and enable preliminary hazard maps to be prepared quickly and at a reasonable cost. Using these methodologies, a landslide hazard assessment and hazard map was prepared for an area of some 880 km^2 in the landslide-prone terrain of the Javorniky Mountains.

1.4 A Hazard Preparedness Strategy

Although earth scientists and engineers may undertake assessments of landslide hazard, the responsible government authorities or departments must apply the available information through appropriate planning policies and other precautions. Sensible planning in hazardous terrain involves developing policies and practices that mitigate the effects of the hazard. In areas affected by slope instability problems, landslide hazard assessments and the preparation of landslide hazard or susceptibility maps provide a sound basis for strategic and regional planning aimed at mitigating the effects of threatening landslide events. Landslide hazard maps are of great value to development planning as they present a spatial division of the ground into areas of different levels of potential threat (landslide hazard zones). It is these divisions, which provide the essential framework for land-use planning, building regulation and the development of appropriate engineering practices.

A landslide hazard preparedness strategy requires government administrators and the general public to appreciate two things: the scale of the existing landslide problem; and the potential for any hazard assessment to assist in dealing with the problem.

The reports and maps derived from the current study are aimed at providing information that will be of assistance to those people charged with incorporating landslide hazard mitigation into a planned, comprehensive, hazard mitigation strategy for Slovakia (and other countries with similar landslide hazards). The objective is to increase awareness of the methodologies for rapid, landslide hazard assessment as an aid to assessing and planning for landslide hazards, and the relative cost-benefits of these techniques. The landslide hazard map of the Javorniky Mountains study area accompanying the report may also be used to guide development and land use planning in this part of Slovakia. The study findings may be viewed as a source of information to complement similar studies undertaken by researchers in other parts of Slovakia.

2 LANDSLIDES IN SLOVAKIA AND THE STUDY AREA

2.1 Regional Setting

The study in Slovakia, central Europe, was initiated by geologists of the Geological Survey of the Slovak Republic (GSSR) with whom BGS had previous research collaboration under an EKHF-funded environmental project. They also selected the study site for landslide research, which constitutes part of the Javorniky Range of mountains forming part of the Western Carpathians arch, which extends from Slovakia to Romania. This mountain chain stretches from west to northeast along the border with the Czech Republic in the west of Slovakia (Kovacik, 1999). The area has high relief and a humid, temperate central European climate. Winters can be severe and the high mountains are snow-covered for 4-5 months a year. In summer, however, temperatures can reach the upper 30s centigrade.

2.2 Landslide Occurrence in Slovakia

Landslide events are recurrent across the Slovak territory as a whole and cause considerable environmental damage. Statistical studies in the State Geological Archive (Geofond) report more than 13,000 registered landslides, which cover about 1620 square kilometres. This represents over three percent of the national land surface. The mountainous uplands, particularly those underlain by flysch deposits, contain slopes with up to 40% landslide movements. Uplands associated with Neogene volcanic rocks in central and eastern Slovakia have up to 60% slope deformation by landslides. The relatively undeformed inner Carpathian flysch deposits and sediments of the Cenozoic tectonic basins have landslide occurrences ranging from 12 to 70% of total slope area.

2.3 Geological Framework

There are two types of flysch deposits in the Carpathian uplands: an outer Zone of tectonised, folded and thrust-faulted Tertiary flysch encompassing the Javorniky Study area (Figure 2.1) in western Slovakia and an Inner Zone of relatively undeformed flysch deposits in central Slovakia. Both sets of deposits comprise kilometre thick sequences of alternating claystone and sandstone with some marlstones and conglomerates. The Outer Zone of Tertiary flysch is tectonically bounded against the Klippen belt of ridge-forming limestones, dolomites, shales and conglomerates of Jurassic and Cretaceous age. Weathering and erosion processes on flysch formations in the Quaternary period, mainly periglacial solifluction, have resulted in soil and regolith profiles that are relatively thin on the higher slopes but may reach up to 10 to 20 metres thickness in the foothill zone.

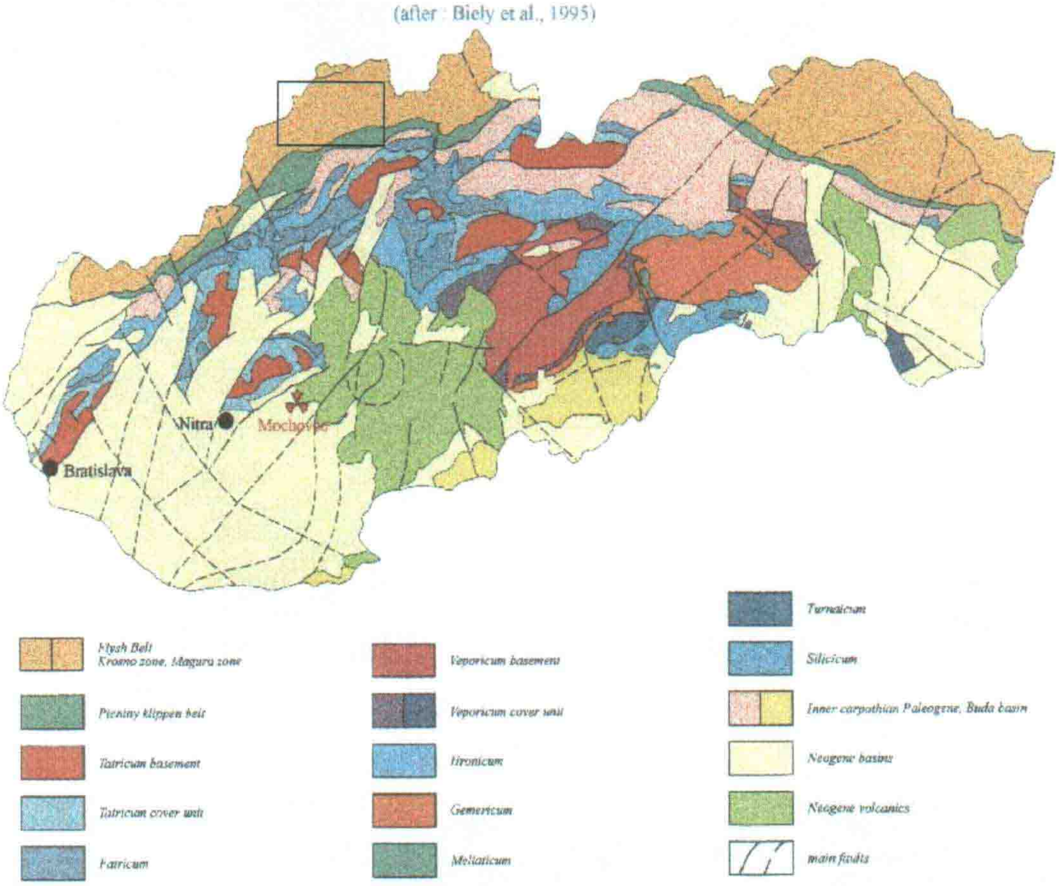

Figure 2.1 Geological and tectonic sketch-map of Slovakia; Javorniky study area outlined by rectangle

The study area envelops the tectonised Tertiary-Cretaceous flysch belts. In the southern part of the study area the geology comprises a folded and faulted belt of Cretaceous flysch strata (the Klippen Belt described above) with limestone units, which are in tectonic contact with a Palaeogene flysch belt of mainly alternating sandstones, shales and marls occurring in the northern part. The flysch belts were deformed by the relatively young Alpine-Carpathian tectonic system. Their composition of alternating sandstone and shale sediments and thin cover soils, combined with weak engineering strengths, high relief and location within a humid, temperate central European climate render these sediments, and especially the shale-rich horizons, prone to landsliding (Malgot and Baliak, 1993).

2.4 Landslides in Slovakia

2.4.1 Landslides in High Mountain Areas

The high mountain areas of Slovakia include: the Tatras Mountains (Gerlachovsky Stit, 2655 m) in the north, bordering with Poland; the Nizke Tatry Mountains (Dumbier, 2043 m) to the south; and the Slovenske Beskydy (Babia Hora, 1725 m), Mala Fatra (Velky Krivan, 1709 m) and Velka Fatra Mountains (Krizna, 1574 m) to the west and southwest respectively. Precambrian metamorphic rocks and Variscan granites occupy the cores of these mountain ranges, whilst tectonic tiers of Mesozoic sediments overlie the crystalline basement around the margins. Neotectonic uplift, combined with glacial and fluvial processes, has formed a high relief region with steep slopes and deep valleys.

Deep-seated gravitational failures are the most common form of slope movement in the high mountain zone and are accompanied by rockfalls, fossil rock glaciers, rock topples and talus creep.

The Tatras Mountains have the highest relief in Slovakia, ranging from 900 to 2655m above sea level, and are prone to various types of mass movement. The Tatras region is composed of a core zone of Palaeozoic crystalline igneous and metamorphic rocks which is overlain structurally by Mesozoic carbonates, inner Carpathian flysch and Quaternary glacial and colluvial sediments. Landslide types include deep-seated failures, topples and rock falls, fossil rock glaciers, block slides, and earth- and debris-flows.

Deep-seated failures reach depths of several hundred metres and may cover some kilometres in spatial extent. These failures occur in both crystalline and Mesozoic sedimentary rocks; the former are controlled by tectonic shears whilst the latter are due to differences in mechanical properties between contrasting sedimentary rock types. Deep-seated creep failure leads to progressive disintegration of mountain ridges and gives rise to numerous rock falls (Kovacik and Paudits, 1998). These creep–type landslide features are clearly defined scarps, which have an anti-dip slope inclination and tend to occur in an *en echelon* array near to the summit of these Alpine mountain crests. A typical example is that of Smrek ridge (2050 m) near to Baranec Peak (2184 m) in the Western Tatras chain. The scarps in this area are 6 to 8 metres deep and extend laterally for 10's of metres. Depressions caused by the scarps are, characteristically, filled with snow until mid summer. Three successive imbricate scarps were observed whilst a fourth made up the main east west facing slope of the mountain ridge. Along the ridge crest and downslope from the crestal zone several 'fissures' or rock openings were noted and seem to have a similar orientation to the main scarps. These fissures are considered to represent incipient rock failures of the same type as the scarp-forming types. Several rock fissures were observed on the opposite Placlive ridge (2125 m) close to the Polish - Slovak border.

The deep-seated slope failures occurring on the south-facing flank of Chabenec ridge (1955 m) in the Lower Tatras Mountains have broadly similar geometry and scale to those of Smrek ridge. Recent research work by GSSR, supported by the University of Colorado, has focused on the excavation of trenches across these scarp features revealing fault gouge and fossil soil remains that were dated by the radiocarbon method at 2000 to 8000-years Before Present (BP). The ridges are thought to have been formed by successive fault movements and seismic activity following stresses created by mountain ice melt and retreat at the end of the last major glaciation. The striking similarity of the rock failures on both the Western and Lower Tatras suggests a common, fault-related origin. This type of slope failure is deemed to be responsible for damage to National Heritage buildings such as the Skalka Monastery in western Slovakia (Vlcko et al. 1996).

Fossil rock glaciers have been reported by Nemcok and Mahr, (1974). Rock glaciers form conspicuous deposits in glacial cirques and at the heads of glacial valleys. The origin of these deposits is related to Pleistocene cold climate processes. Warm periods at the end of the Würm glaciation favoured the formation of rock glaciers in the Tatry and Nizke Tatry Mountains.

Block slides are recorded in the central elevated part of the Tatras Mountains. The heterogeneous nature of competent limestone and incompetent argillaceous rocks in the Mesozoic rocks of the high mountain zone has promoted the development of creep failures on slopes, which grade into rockfalls. Large blocks of competent units (limestone, dolomite) that lie parallel to the slope are separated, usually along tectonic faults, and then creep downslope over argillaceous and schistose strata. Up to 190 such rockfalls have been recorded in this geological region.

Debris flows are common in the central and marginal valleys, where they are mostly generated by storm floods. They have variable morphology ranging from simple, forked to tree-shaped forms and can destroy infrastructure such as tourist buildings, which are common in the Tatras National Park area. Earthflows occur mainly in the Paleogene flysch deposits in the western and south-western parts of the mountain zone. The clay-rich flysch deposits are also prone to furrow and gully-type erosion.

A slope failure index map of the Tatras region was compiled from photogeological interpretation, field work and published information (Kovacik and Paudits, 1998). All slope failures, with the exception of debris flows and avalanches, are classified as dormant. The latter are considered to be in an active state, particularly during heavy rainfall and meltwater flow in spring and summer. The deep-seated, gravitational failures are thought to be in a state of extremely slow movement. Landslides in flysch strata are triggered by heavy to extreme rainfall events, snowmelt, gully erosion and, to some extent, woodcutting. A zonation of slope stability was produced in terms of stable, relatively stable and unstable areas. The unstable area comprises about 10% of the Tatras area and contains mainly deep-seated failures, combined with topples and rockfalls in Mesozoic sediments. Debris and earthflows are more abundant in areas of Palaeogene flysch.

Due to the scale of the map, the rock/debris dynamics and hazard zones represented by debris flow deposits and erosional furrows and gullies are identified on satellite optic images. This study was extended to other parts of Slovakia and resulted in the compilation of a series of environmental maps at a scale of 1: 50,000. These included: an engineering geological zoning map; a map of the susceptibility of the area to landsliding; a map of the susceptibility of the area to soil collapse (loess); and a map of the important geological factors in this environment. The latter shows geological features with the potential to form a hazard and barriers like tectonic lines, epicentres of recorded earthquakes, seismicity, slope failures, erosion features, weathered rocks, low load-bearing capacity of foundation soils, resources of raw materials including water, landfill sites and other sources of possible contamination.

2.4.2 Landslides in Cenozoic Tectonic Basins

Much of the Slovak territory is underlain by fault-bounded sedimentary basins filled with Tertiary and Quaternary sediments. The sedimentary infill comprises clays, silts, marly shales, sandstones of Carpathian Flysch derivation, together with glacial and periglacial gravels and, in some local basins, volcaniclastics. Mineral springs located along fault planes within the basins generate travertine carbonate plateaus. These sedimentary sequences produce a hilly topography with wide flat ridges and hills supporting modest step-like slopes and broad valleys. Most of the slope movements take the form of landslides or surficial creep. The Quaternary deposits become saturated with groundwater, especially at the interface with the flysch sediments, and this activates slope movements. Headward extension of sliding follows a line of the groundwater and thus the slide acquires a stream-like shape.

Surficial creep-type landsliding takes place at the foot of slope depressions, caused by seasonal rainfall and temperature fluctuations. Lateral stream erosion on the tributaries of major river systems such as the Váh and Poprad rivers activates medium scale slumps and elongated, so called frontal, landslides. Such erosive processes may have contributed to slope instability in the Váh reservoir used for a water plant and hydroelectric power (Drusa et al. 1993). Landslides are the most prevalent form of slope failure in the intra-Carpathian lowlands.

Lateral spreading rockslides and rock toppling occur in the Drevenik area east of the Poprad and Levoca districts. In this area outcrops of flat lying travertine limestone overlie undeformed clay-rich flysch formations; the limestones are strongly jointed and erosion has led to progressive tilting of isolated marginal blocks and boulder scatters across the surrounding farmland. Movement of the travertine foundation of nearby Spis Castle, a Slovak National Monument, over the plastic clay substratum has caused collapse of parts of the building (Vlcko, Baliak and Malgot, 1993). Rock toppling at a less advanced stage of movement is recorded in roadside exposures of a thrust-faulted boundary between Triassic limestones and Cretaceous shales north of Ruzumberok town.

2.4.3 Landsliding in Areas of Miocene Volcanics

Volcanic activity mainly in the Miocene, produced stratovolcanoes consisting of piles of andesite, tuffs, rhyolites, basaltic andesites and their tuffs. Slope failures appeared where lava flows and tuffs rest on Tertiary clays, silts and marls. The area of greatest intensity of landsliding lies on the margins of neotectonic elevations whose slopes dip toward erosive depressions and valleys. The margins of volcanic plateaus are strongly fractured and large blocks of volcanic rock have been displaced by slow creep movements which give rise to irregularly distributed block and boulder fields mantling the lower slopes and depressions. Locally the movement of large blocks of competent volcanics by deep-seated creep becomes transitional to rockfalls and appears to affect the marginal zones of volcanic complexes, which are thought to be thinner in size than the central parts. Landslides which initiated as this type and graduated downslope to debris flows, and which had a catastrophic effect on property and infrastructure, occurred in Handlova town and Podhradie village in the central districts. The transported material in both cases was a mixture of volcanic blocks and gravels, which slid across claystones and sands, which, in turn, overlie coal-bearing strata. Up to 150 houses, sections of road, water supply and power lines were destroyed by this event. A combination of subsidence caused by underground and open-pit coal mining and lubrication along spring lines appears to have been the main triggering mechanisms in both the Handlova and Podhradie slides. Another example is that of Pokoradzska Tabula Plateau, an area of volcaniclastic rocks underlain by clay-silt sediments of about 130 sq km, which was heavily undermined by landsliding activities and caused, in part, by human interference in deforestation and road construction (Hrasna et al, 1993).

These catastrophic landslide events prompted the first national inventory of landslides in former Czechoslovakia in 1962/1963. It was accomplished through field and aerial photograph studies. A second major inventory of landslides was undertaken between 1981-1991 using aerial photography and new topographic maps at 1: 25000 and 1: 10000 scales. All of the recorded landslide data is held in digital format by GEOFOND, Bratislava (now a component body of Geological Survey of Slovak Republic, GSSR) and can be accessed by the commercial or public sector.

2.4.4 Landslides in the Javorniky Study Area

The types of landslide that occur in the tectonised Flysch zones are rock and block slides, earthflows and minor soil creep phenomena (Figure 2.2). These landslides are morphologically distinct and more than 4000 individual earthflows have been recognised in the Flysch belt, in an area of 880 km^2.

Mass movement of the earthflow variety is prevalent in these ranges and is characterised by complex hummocky landforms with intervening marshy sinks or ponds. Irregular vegetation or the general absence of cultivation on these transported soils often distinguishes such hummocky landforms.

Reactivation of earthflow deposits is widespread, often occurring in response to seasonal increases in pore-water pressures due to high spring or winter rainfall and spring snowmelt. Where reactivated movements occur on road cuttings the depth and flow geometry of the displaced material can be readily seen on these exposures. Much of the high ground in the Javorniky range is forested and this vegetation cover plays a critical role in stabilising soils and slopes. According to GSSR information, forest cutting in this area began in the 17th Century (the so called "Valachian colonialisation"). At that time large parts of the forests were cut in order to increase the area of arable land. This process has continued, to a lesser extent, to the present day leaving an irregular patchwork of open grassy slopes. Mass movements, as indicated by the irregular topography and lack of cultivation, affect a considerable amount of open and forested ground. It is suggested by GSSR geologists that the earliest slope movements took place at about 11-12000 years BP following the thawing of the permafrost ground, especially on the higher slopes. Generally the high angle slopes are founded on sandstone features and are relatively unaffected by landsliding. Slope failures in recent times have, evidently, been triggered by heavy spring rainfall and snow-melt leading to groundwater saturation of clay-rich soils covering the claystone bedrock that forms the gentler slopes (O'Connor, 1999).

Figure 2.2 Earthflow type landslide shown by hummocky landform and irregular vegetation

A central elongate north-east trending belt of the Javorniky range, characterised by Quaternary clay- and clast-rich soils that produce gentler slopes, is referred to locally as "Podjavornika brazda" or depression zone. It is affected by prolific landsliding events. This major topographic feature was clearly discriminated on radar imagery supplied by GSSR. The depression zone coincides with a major tectonic junction occurring between the Tertiary Flysch and Jurassic and Cretaceous Klippen belts and it illustrates the important influence of the underlying geology on the extent of landsliding phenomena in the region. The best documented example of earthflow and debris flow landsliding in this belt is that which encroached on Kliestina village in 1983 (Kovacikova et al. 1989)

Rock and block slides occur along weaknesses between competent sandstone and less competent marlstones and claystones and especially along lithological interfaces that have been exploited by consequent drainage systems running parallel to bedding and fold structures. Kovacik (1991) describes a large-scale rockslide occurrence on the eastern flanks of Mincol (1273 m) in the Slovenske Beskydy Mountains. Earthflows and superficial creep movements are the most common types of slope deformation in the Carpathian uplands (450 – 600m) but are less common on the highland watershed areas (800 – 1000 m). Most of the landslides in the upland flysch areas are concentrated in zones where systems of parallel ridges and depressions are cut by transverse valleys. Lithology and morphology control the development and distribution of earthflows. Thicker, illite-rich, clayey superficial deposits with moderate concave slopes and high watertable levels favour landslide movement. These deposits frequently overlie marlstone and claystone lithologies and when the latter dip downslope they give rise to greater landslide occurrence. Extreme rainfall, erosion, and human activities are factors that can reactivate older landslides on upland slopes.

3 THE REMOTE SENSING AND GIS METHODOLOGY

3.1 Rationale

The ability to map landslide hazards rapidly over wide areas relies on a combination of remote sensing and spatial analysis techniques, performed using image analysis and geographic information systems (GIS) software.

Firstly, appropriate remotely sensed data must be acquired for the study area. This is then interpreted to produce a landslide inventory, taking into account any existing information on their distribution and with a minimum level of field checking being used to support the interpretation. Maps of potentially unstable ground conditions and possible triggering mechanisms are digitised ready for analysis in the GIS. The inventory is then compared statistically to each digitised layer and a weighted significance attached. This is a measure of the association of each surface material with the existing landslides. The weighted layers are then reclassified in terms of landslide susceptibility, before they are combined to form the overall susceptibility map. The hazard can be presented to the target audience in a variety of ways. The risk posed to infrastructure can be assessed qualitatively by including key roads, railways, settlements and other cultural features on the final hazard map.

Image analysis and GIS software is increasingly available at low cost and can be run on inexpensive personal computers. The two methods of analysis are merging, so that image analysis software often contains GIS functionality and vice versa. Both types of software also include sophisticated cartographic output capabilities. Because of the need to know the hazard value at every point on the surface, the hazard analysis is best performed using a raster GIS. These systems operate on grids of contiguous data values recorded for every point in each digitised file. Vector GIS is less suited to this type of spatial analysis, because it divides the surface up into a series of components represented by discreet vectors and polygons. It is however useful for the production of final map output, because roads and other important elements of infrastructure can be conveniently displayed as vectors.

3.2 Remote Sensing

The term remote sensing covers a range of systems that can be used to provide information about the Earth's surface from satellite or aircraft platforms. The most familiar types of data are colour and black and white aerial photographs. These have been a valuable source of data in geological studies since at least the mid-1900s. Similar optical imagery, albeit with much reduced spatial resolution, became available from satellite platforms in the 1970s. For over 15 years, affordable repeat coverage from optical and radar sensors in Earth orbit has been available to scientists. As sensor technology has advanced, so spatial resolution has increased.

Two main factors guide the selection of data for landslide hazard studies; the scale of the landslides to be mapped and the climate of the study area. Until recently, only the largest landslides could be studied using satellite data because the resolution of the systems in orbit was insufficient. For most of the smaller landslides, data from photographic aerial sensors had to be used in order to resolve the features of interest. New high resolution satellite systems such as IKONOS are changing this, but for many regions aerial photography are readily available and will remain a key source of information for years to come. The main problem occurs in tropical regions with persistent cloud cover. In such regions radar data, which penetrate cloud, are a valuable additional information source.

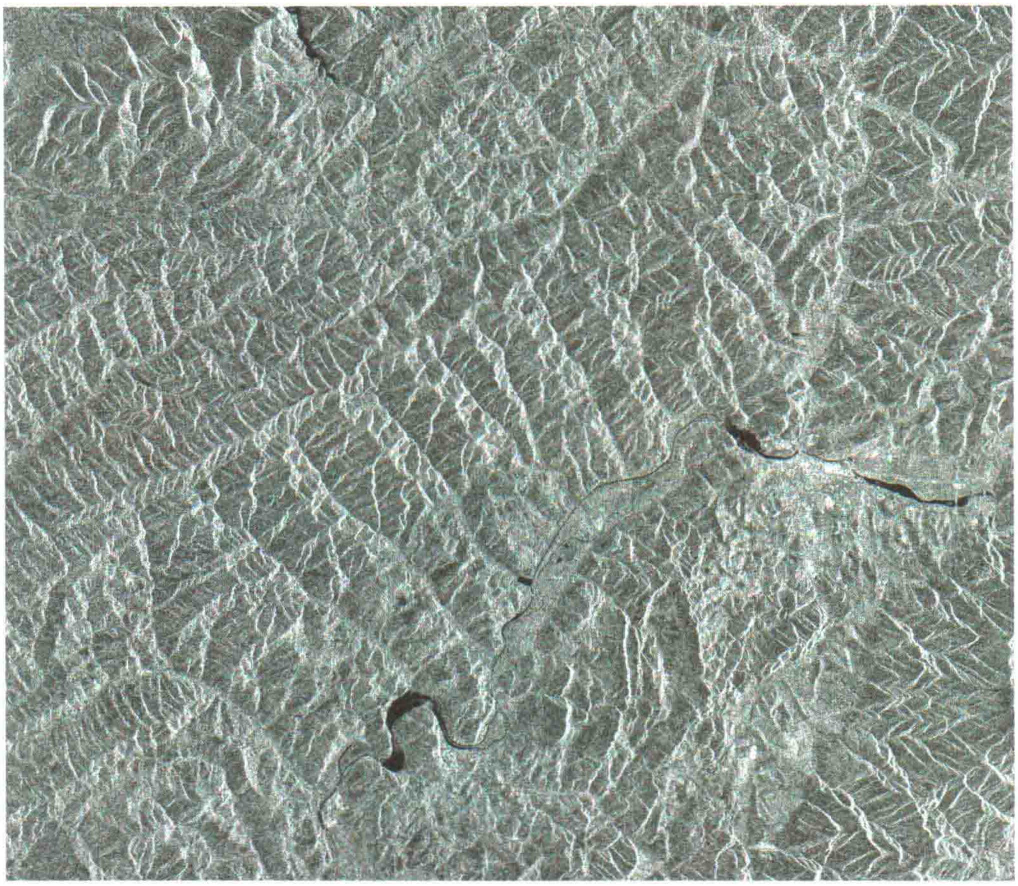

Figure 3.2 ERS 2 radar image of Javorniky Range. The "Podjavornika brazda" or depression zone is visible to the northwest of the Váh river.

It is possible to process the aerial photography in a digital environment. This involves scanning the prints or negatives and adding information about the orientation of each image in three dimensions. Sophisticated software can then be used to remove all the geometric distortions inherent in aerial photographs. At the same time, a digital elevation model is created and the imagery can be viewed in stereo on the computer display. This process results in orthophotographs that are true to a map base. Interpretation can proceed within the digital environment and map-accurate linework can be captured directly. This approach uses relatively expensive computer hardware and software, however, and so it was not followed in this project. It could be considered in the future as the costs of software fall. One of the principal advantages of this would be that the digital elevation model, created as part of the photogrammetric process, is one of the data layers that is always required for the GIS analysis.

In the present study, the aerial photography was analysed in analogue form using a conventional mirror stereoscope. It was acquired in 1992 at a scale of 1: 27500 and was provided by the Military Topographic Institute in Slovakia for this project. In total 83 landslides were identified in the study area using the aerial photography. The difficulty of identifying landslides in forested areas may have introduced a spatial bias and this must be borne in mind in the final analysis. The first interpretation step was to agree on a classification procedure for the landslides. In this study, a simple approach was used whereby each landslide was identified by a point placed somewhere within the disturbed material, irrespective of the style of landslide or the area covered by the debris. This information was recorded manually before being transferred to a map base and digitised. The interpreted slope movement data, annotated on the photography, was transferred via on-screen vector annotation to a

Although remote sensing offers a convenient way to map disturbed ground over wide areas, the methodology contains certain assumptions. These are: (1) that landslides can be reliably identified and in a consistent fashion by all researchers in a team; (2) that triggering mechanisms remain the same over time; and (3) that the ground conditions that were previously susceptible to landsliding continue to be so. It is therefore essential that the interpretation is checked against both the existing, local knowledge of the problem and field conditions during the study. Field checks to provide such "ground truth" should be a key step in the interpretation, leading to iterative improvements in the landslide inventory as knowledge of the problem increases.

3.2.1 Applicable Remote Sensing Data Types in Slovakia

The Slovakian climate gives sufficient cloud free days for both optical and radar data to be of use. The main factor governing the selection of data type is the scale of the landslides to be mapped. As in the Jamaican study (Northmore, 2000), the small scale of many of the landslides makes aerial photography by far the best data to employ for detailed mapping in this region (Figure 3.1). Satellite radar data were used to give a regional overview (Figure 3.2), and display the tectonic depression zone to good effect, but have insufficient resolution to be used to prepare the full landslide inventory.

3.2.2 Data Processing and Analysis

Selection of aerial photography as the main input data set for creation of the landslide inventory determines the processing and analysis strategy. Various routes are eliminated and so will not be considered further in this country-specific report.

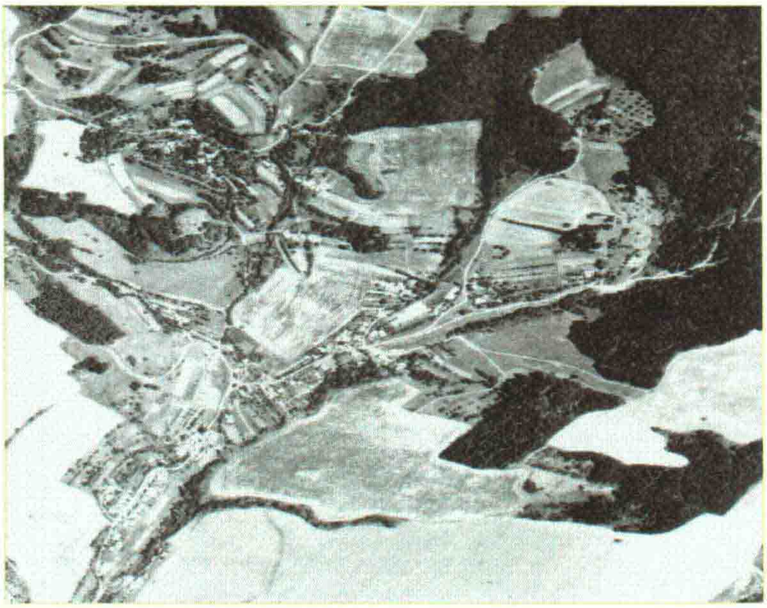

Figure 3.1 Extract from aerial photographic image of Miskovci village and surrounds, central Javorniky Range, Slovakia. Mottled texture, morphology and clustered vegetation indicate landslipped ground

georeferenced KFA 1000 Russian satellite panchromatic image. This has a ground resolution of 5m. The KFA scene 19343 film 0093 was acquired on 29 August 1990 (Figure 3.3).

Figure 3.3 Georeferenced KFA 1000 panchromatic image of Javorniky Range study area. Data has a ground resolution of 5 m. The KFA scene 19343 film 0093 was acquired on 29 August 1990

More complex classification schemes can be followed that record other useful information, such as the co-ordinates of the initiation point, the shape of the landslides and the area covered by their debris fan. The simple approach followed here has the advantage of producing a uniform landslide inventory that is easily understood. It also makes subsequent GIS analysis relatively straightforward. Interpretation of these aerial photographs relied on a certain amount of field verification in Slovakia. It also drew on accumulated local knowledge within the GSSR, the main collaborating organisation for this study. GSSR geologists worked closely with BGS staff on all aspects of this study, both within Slovakia and in the BGS image analysis laboratories in Keyworth.

3.3 GIS Analysis

The hazard analysis relies on the statistical comparison of the landslide inventory with various layers of information. A layer constitutes a map on a particular theme, such as geology and is typically split into a series of classes, which could be different lithologies within the map. The analysis could be done manually in principle, but it is a much more powerful analytical method when undertaken digitally within a raster GIS environment. In this scenario, each map is digitised so that it contains *nominal* data in *raster* format; that is, a regular grid of data points within which a particular number represents each class. Once all themes are geographically referenced, the GIS can be used to carry out complex spatial correlations so that the significance of each class within a theme, or even of multiple classes in combined themes, can be assessed objectively. No prior knowledge of the causative factors need be assumed. After this significance has been established, the layer can be reclassified in terms of landslide susceptibility and the susceptibility maps mathematically combined to give an overall susceptibility value at each point within the study area.

3.3.1 Data Layers Used in Slovakia

The choice of map layers to include in the analysis depends on what controlling factors are considered important in the local context. Seven thematic layers were available in the Slovakian study. These were geology, elevation, slope angle, slope aspect, precipitation, forest cover and photo-lineaments (faults and fractures interpreted from the satellite images). Seven themes were used in the final analysis. This is explained using examples from key themes in chapter 4.

3.3.2 Analysis Approach

In the Slovakian study, a simple cross-tabulation approach was used to judge the significance of each class within each theme. More complicated statistical methods can be used and are described in the full implementation strategy (Greenbaum *et al.*, 2000). In the cross-tabulation approach, the landslide inventory is considered a theme with two classes, landslide and not landslide. It is cross-tabulated with each controlling factor theme in turn and the area of landslide within each class measured. If the area is greater than the average area of landsliding in the theme as a whole, that class is considered more susceptible to landsliding than the average. This susceptibility must be assessed in a consistent way, so two other factors are taken into account. Firstly, the overall significance of a particular theme, such as geology, must be estimated. This is done using a statistical correlation co-efficient that varies from 0, indicating no correlation, to a maximum of 1. In the case of Slovakia, geology has a co-efficient of 0.3892, showing that it is more significant than slope aspect, which has a co-efficient of 0.0153. It was therefore given more weight in the final model. In the same way, the significance of each class within a theme must also be assessed. In the case of Slovakia, this was done using a factor called association that varies from -1 (maximum negative association with landslides) through 0 (no association) to +1 (maximum positive association). The method is explained in full in the implementation strategy (Greenbaum *et al.,* 2000).

Having assessed each theme separately, the next step is to assess their combined effect. Each theme is reclassified as an association map and then weighted by its correlation with landsliding. They are then summed and the result is normalised by the sum of the correlation coefficients. This results in a landslide susceptibility model with values of between -1 and +1 that can be interpreted in the same fashion as the individual association maps.

3.4 Outputs, Visualisation and Validation

The final hazard model should be output as a full map, depicting appropriate cultural and geographical reference information. It will depict the hazard zones calculated in the GIS, the topography as contours or as a shaded relief image, and appropriate map data such as roads and habitation. The Javorniky Mountains Hazard Map is described in chapter 4.

The GIS can also be used to visualise the hazard in various other ways. It is possible to create perspective views of the hazard zones draped on the digital elevation model, for example. Fly-through movies can be generated to give a helpful perspective on the hazard in particular areas and its relationship to the controlling factors. These visualisations help get the information across to non-scientific users. They can also form part of the validation process. The final hazard map should be compared with the landslide inventory closely. If it does not predict landslides where they actually occur, the analysis is suspect. Better still, it should be compared with an independent source of information, such as a landslide inventory for an area of interest within the region that was created by field surveying alone.

4 THE JAVORNIKY MOUNTAINS LANDSLIDE HAZARD MAP

4.1 Introduction

The rationale and methodology of landslide hazard assessment leading to the preparation of the landslide hazard/susceptibility map for the Javorniky Mountains study area are described in the previous sections of the report. Fundamentally, the hazard assessment was based on statistical correlation of existing landslide distribution with seven factors, or themes, which were considered to influence landslide occurrence in the area. These factors were geology, elevation, slope angle, slope aspect, precipitation, forest cover and photo-lineaments (faults and fractures interpreted from the satellite images) The resulting hazard map, prepared at a scale of 1:75 000, accompanies this report. Figure 4.1 shows a smaller representation of this map. To assist in visualising the hazard zones in relation to specific topographic elements in the area, the zones are presented as a 'drape' over a shaded relief base and displayed in perspective view (Figure 4.2).

4.2 The Hazard Map

The following themes were available for the study area:

Theme	Comment
Geology	Greatest correlation with landslides. In particular a high proportion of landslides in trough running east/west across the study area (claystones). Lesser relationship with marly limestones (Figure 4.3).
Elevation	The majority of landslides occur below an altitude of 700m. It is possible that the woodlands on slopes above 700m have a stabilising effect (Figure 4.4).
Aspect	Weak correlation with landslides. Some association can be seen as a higher than normal number of landslides occur on slopes facing east through to south-west
Slope	Some correlation with landslides. Indicates that landslides occur most often on shallow slopes (less than 20°) (Figure 4.5).
Precipitation	Little relevance in this case study possibly because rainfall does not vary greatly over the study area i.e., from 110 -> 150 days with precipitation of over 1mm
Forest cover	Strong correlation between no forest cover and landslides as forest has a stabilising effect (could also be partly because it is difficult to identify landslides through forest cover: Figure 4.6).
Photo-lineaments	Strong correlation between photo lineaments and landslides. The majority of landslides occur within 400m of a photo-lineament (Figure 4.7).

The final hazard map was created from a combination of all 7 themes. The high hazard is in the south, particularly in the south-west. This shows a strong correlation with geology, which is the main controlling factor in this study area. The weaker correlation with forestry (fewer landslides in forested areas) may reflect the stabilising influence of trees, or it may reflect a bias in the input data caused by the difficulty of mapping landslides in these areas using aerial photography.

The final hazard map can be validated in several ways. It can be compared to the input landslide inventory to check whether it correctly predicts the observed hazard that was used to form the model. This is a check of the methodology. To check the results, the hazard map can be compared to the landslide inventory collected using conventional methods in the field. The landslide polygons in this fieldwork-derived inventory correlate very well with the zones of high hazard on the map. The ultimate test would be to extend the analysis to an unknown area and then check the validity of the predicted landslide hazard in the new area using field surveying.

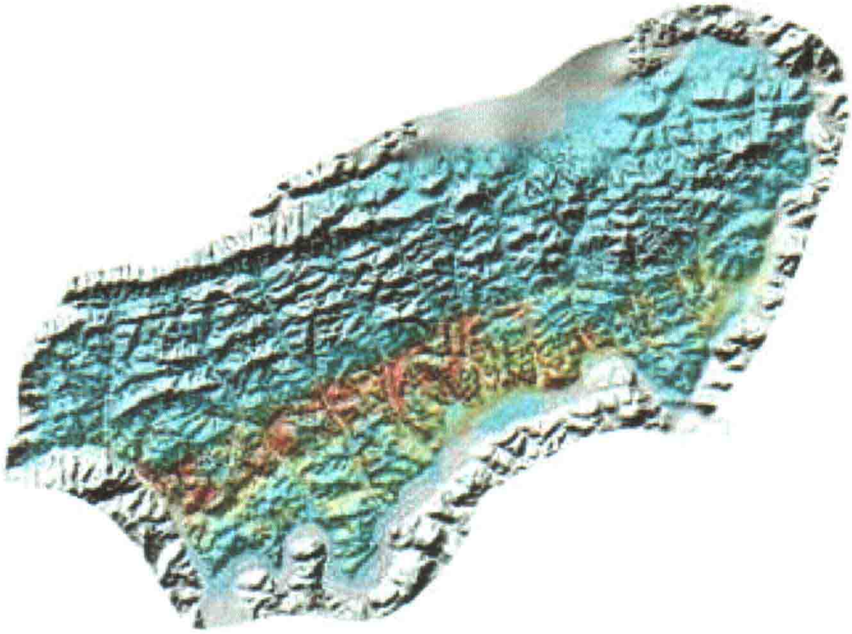

Figure 4.1 Landslide hazard/susceptibility map for the Javorniky Mountains study area. Coloured areas represent differing levels of susceptibility: red=high, yellow= moderate, blue= low, grey within blue=minimal

4.3 Use of the Hazard Map

Four levels of susceptibility to landsliding have been identified on the Javorniky Mountains landslide susceptibility map, namely:

ZONE 1 Areas of generally **high landslide susceptibility** within which significant landslide activity is likely to occur. Although some safe locations may exist, many areas will present unacceptable risks. The vulnerability of existing buildings, infrastructure, access routes and critical services should be critically assessed as a matter of priority and specific risks identified. New building or development should be restricted and planning permission subject to expert site evaluation and approval.

ZONE 2 Areas of generally **moderate landslide susceptibility** within which local and possibly some widespread landsliding is likely to occur. This zone will contain a mixture of higher and lower risk areas. An assessment of risk to existing infrastructure is recommended. The vulnerability of access routes and critical infrastructure should be considered in regional contingency planning. Expert advice should be sought when planning new developments and restrictions should apply.

ZONE 3 Areas of generally **low landslide susceptibility** where some local landsliding is possible. The vulnerability of existing structures should be assessed where site stability gives cause for concern. New developments in this zone may be unrestricted but should take account of local site conditions and, where uncertainty exists, expert advice should be sought.

ZONE 4 Areas of **minimal landslide susceptibility**. Relatively minor failures may occur along banks of streams and road cuttings but generally, low slope angles will preclude landslide initiation across this zone. Nevertheless, the vulnerability to disruption of access routes from zones of higher landslide potential should be considered as part of the contingency planning process.

The zones imply relative (not absolute) hazard or susceptibility only and do not imply any legal restriction or regulation by zoning ordinances or laws as laid down by local government authorities.

Also shown on the main hazard map are certain cultural and infrastructural features. These are essential elements in risk assessment and are presented on the map to enable the user to make a preliminary assessment of their relative susceptibility to landslide hazard in the area.

The map is intended primarily for the assessment of landslide hazard on a regional scale. It indicates indirectly the extent and relative severity of landslide hazard. For regional planning purposes, the map may be used as a tool to assist in the:

(a) recognition of geographical areas where landsliding has already occurred and future landsliding is most likely. In other words, the maps help in understanding the constraints on land use and the scale of the landslide problem, and thus can assist in land-use planning by relating land-use zonation to hazard zonation

(b) evaluation of the likelihood of hazardous events occurring as a consequence of proposed developments (*environmental impact assessments*)

(c) assessment of hazard potential with regard to proposed developments so that future losses can be minimised by relocation (hazard avoidance) or the adoption of protection measures

(d) identification of areas where detailed geological/geotechnical investigations are desirable prior to development.

(e) enhancement of public education

When using the landslide susceptibility map it should be understood that natural changes, as well as those induced by human activity, could affect the susceptibility to landslides in any area. The absence of past or present landslides does not mean that slope failures will not occur in the future.

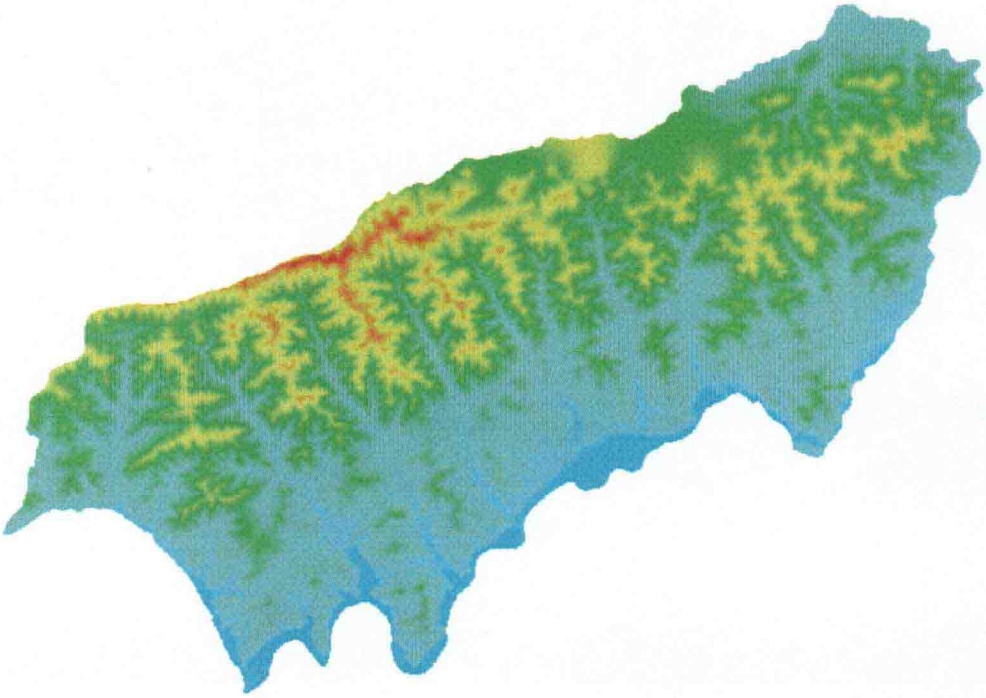

Figure 4.4 Elevation map of the Javorniky area. Red= 900-1000 m, yellow=600-900 m, green=400-600 m, blue= 300-400 m O.D.

Figure 4.5 Map showing distribution of slope in the Javorniky area, calculated from digital terrain model. Yellow=steep, green=moderate, blue=shallow

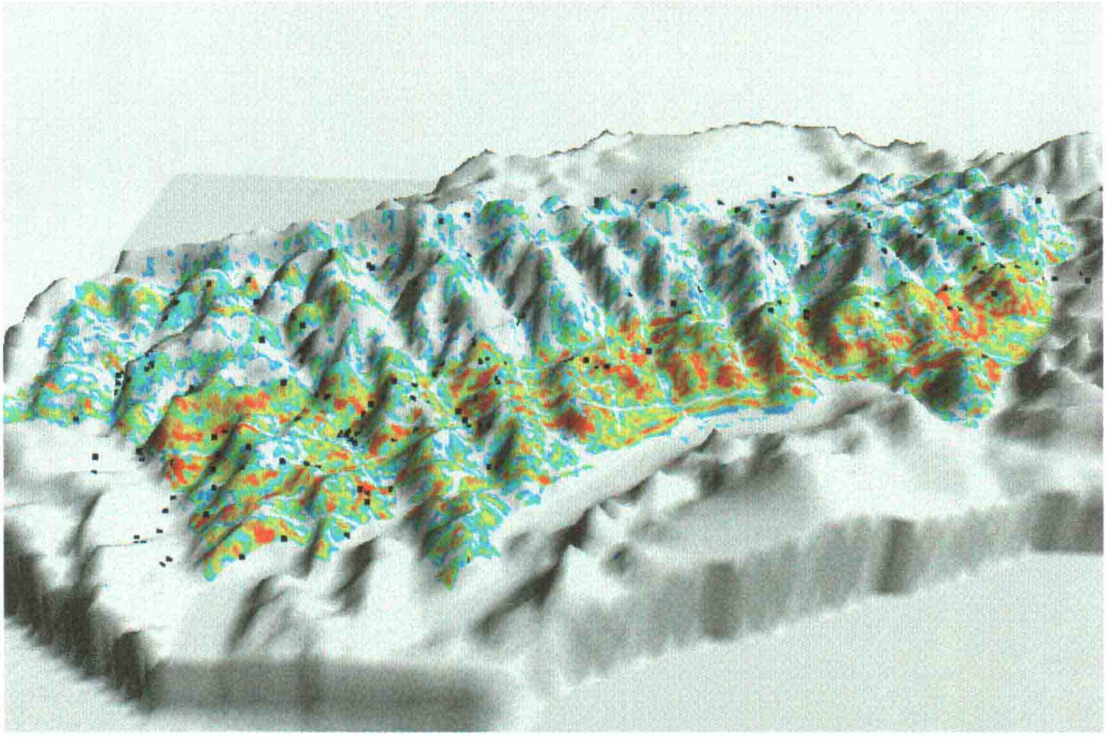

Figure 4.2 Landslide susceptibility zones of the Javorniky area are presented as a 'drape' over a shaded relief base and displayed in perspective view

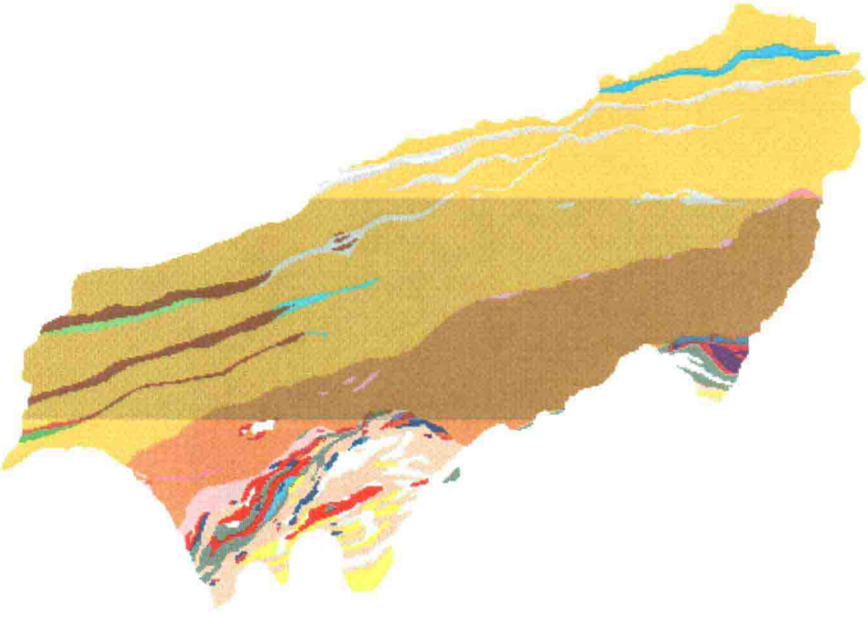

Figure 4.3 Geological sketch map of the Javorniky area. Key to colours: variegated colours=Cretaceous Klippen Belt limestones and interbedded clays; pale brown=claystones; beige with brown and green-cyan stripes=Paleogene flysch deposits with claystone beds

Figure 4.6 Distribution of forested ground (green) and cleared areas (beige)

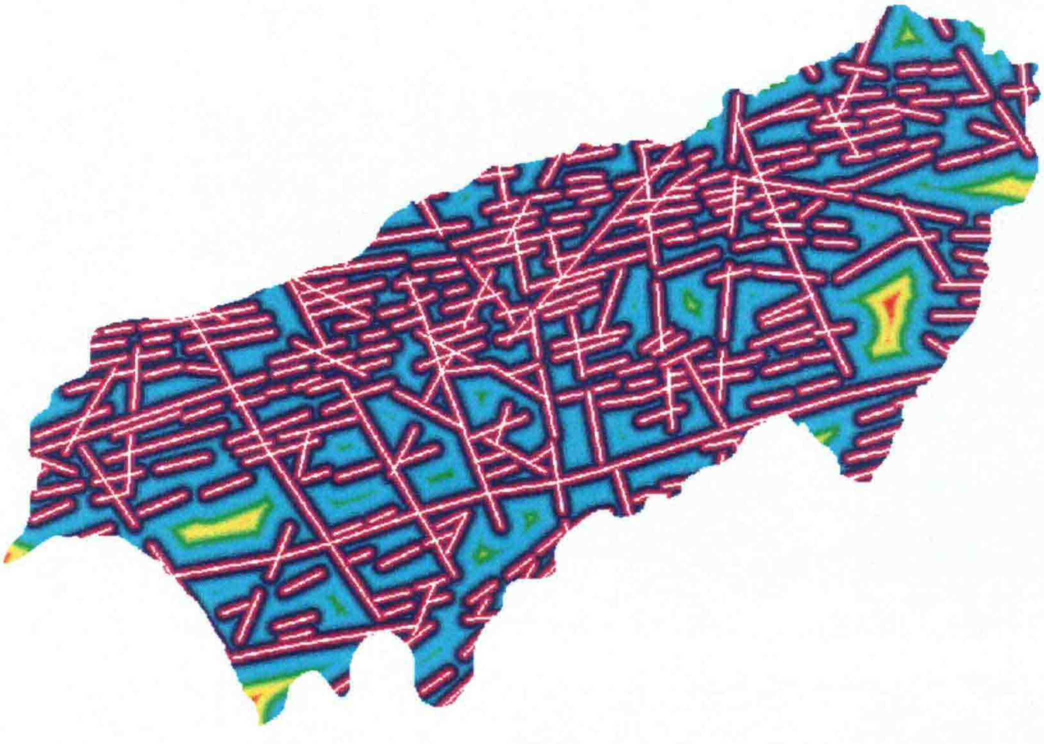

Figure 4.7 Map showing distances from photolineaments

4.4 Limitations of the Hazard Map

The landslide hazard map does not predict when or exactly where landslides will occur during a specific triggering event, or events. The hazard zones represent the differences in the chance of landslide occurrence that can be expected over the long-term.

The map can be used for preliminary regional assessments only, and should not be used for any purposes over and above that determined by the map scale. Specifically, the map is unsuitable for site-specific stability assessments, for the siting of individual structures or for engineering design. More detailed local hazard assessments are required for these purposes. The map in no way replaces or reduces the need for new developments to be designed on the basis of an appropriate geotechnical investigation. The map serves to focus attention on likely problem areas that should then be assessed in detail, before new developments occur, using site-specific geotechnical techniques.

Like all maps, the landslide hazard zonation is only as good as the data from which it is compiled. The generalisations required to delineate map units means that specific locations within those units may in practice have a different hazard susceptibility than that indicated.

If the limitations on use and accuracy of landslide susceptibility maps are appreciated, they can provide an extremely effective basis for landslide hazard management and land-use planning. Advances in remote sensing techniques and Geographical Information Systems (GIS) technology now make rapid and cost-effective production of these maps viable. By following an established methodology, rapid assessment of areas with limited existing data, leading to the production of 'preliminary' or 'first-stage' susceptibility maps, is possible. GIS capability allows map accuracy to be readily updated, or the scale of production changed, as additional data are acquired. It would be of considerable benefit to Slovakia if resources and expertise were directed toward promoting 'in-house' GIS capabilities for landslide hazard assessment and hazard map preparation. The GSSR has developed considerable expertise and experience of landslide hazards in the region. Enhanced GIS-based capabilities for hazard assessment would complement this expertise and assist in building a sound framework for developing and implementing effective, hazard preparedness strategies.

5 CONCLUSIONS AND RECOMMENDATIONS

This report describes the preparation of a landslide hazard map for the Javorniky Mountains study area in Slovakia. A rapid, cost-effective method for landslide hazard mapping has been developed. It is based on the principle that the past is the key to the future. A landslide inventory depicting past landslides in the study area was created partly using remote sensing and partly also by conventional field observation. This was then used as one of several input data layers within a GIS to model the future hazard for the study area. The inventory was statistically compared to various thematic maps to establish the likely controlling factors on the occurrence of landslides in the area. These were then used to weight the input thematic map layers in terms of landslide susceptibility. The final landslide susceptibility map was created by combining seven layers, of which the most important was geology.

The resulting landslide hazard map depicts broad zones of landslide hazard across the region. Validation against local knowledge of the study area and against the landslide inventory itself suggest that the map is a reasonable first iteration on which it will be possible to build in the future as more information becomes available. It forms a useful tool to guide the planning process and the siting of more detailed ground investigations. It must be remembered that it does not indicate the actual hazard for any specific locality. There is a clear correlation between certain geological formations and increased landslide susceptibility in the area. Topography is also a controlling factor, with slides occurring on steeper slopes in many settings. Faulting and depth of weathering also appear to be important factors. Many of the slides are shallow debris slides involving weathered bedrock material over certain lithologies. It is therefore probable that these formations possess lithological characteristics that promote deep weathering and make them vulnerable to landsliding when triggering events such as intense storms occur or when spring snowmelt saturates the soil.

The creation of the map is only one step in the establishment of a mitigation strategy. Many of the others lie beyond science within the realms of local planning procedures and the political and legislative process. These issues have also been described and they are discussed at greater length in Greenbaum et al. (2000). The methodology described in this report is no more than a skeleton on which to build a national landslide mitigation strategy that takes into account a variety of local factors. These include:

- Differences in the local controlling factors and triggering events
- Related differences in the style and scale of landsliding
- Climatic and geographic variations
- The optimum local choice of remote sensing data type
- Availability of the necessary thematic maps layers for the GIS analysis
- The presence of an appropriate local technical skills base
- Local computer hardware and software systems and support
- Political and legislative constraints
- Adequate funding

The use of the map resulting from this study should take into account all these local factors.

The local nature of controlling factors can be illustrated by comparing the Slovakian situation with that in the other study sites used during this research. In Jamaica, geology was very important. The majority of slides occurred on the steeper slopes, and they were strongly associated with certain lithologies. The character of these earth movements was also quite different to those found in Slovakia, with more discrete landslides compared to the moderately disturbed ground occurring over wide areas in Slovakia. Fiji was similar to Jamaica, but the over-riding controlling factor was intense rainfall events that can trigger landslides in most terrain types. These local differences in controlling factors and triggering mechanisms are perhaps illustrated best of all by the studies in Papua New Guinea. Here the slides are very large indeed, and can be mapped easily using low-resolution satellite data. The most important triggering mechanism is earthquakes and the slides are strongly controlled by the rugged terrain, with extreme elevation and very steep slopes being common.

Whilst local conditions do vary, the same approach to landslide hazard mapping has been followed with reasonable success in each country by adapting it to fit the local circumstances. This indicates that the aim of developing a generic approach has been achieved.

The map should be utilised and then perhaps developed further by all those concerned with landslide hazards in the region. The importance of collaboration between all the interested parties and the involvement of the likely users in the process cannot be overstated. This will ensure that the products are useful and understandable by those they are intended to help. It will also create a feeling of shared ownership and thus encourage take-up. The success of this project should not be judged solely on the validity of the final hazard map. A more important measure is perhaps the degree to which the map is subsequently used and built upon.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

Drusa, M., Stofko, S., Bartunek, J. and Matejcek, A. 1993. Slope stability of Zilina Water Plant. *Seventh International Conference and Field Workshop on Landslides.* S. Novosad & P. Wagner (editors). A.A.Balkema, Rotterdam-Brookfield.

Greenbaum, D. G, O'Connor, E. A., Northmore, K. J., Jordan, C. J., Marchant, A. P., Marsh, S. H. and McDonald, A. J. W. 2000. An implementation strategy for landslide hazard preparedness. *British Geological Survey Technical Report* WC/00/8.

Hrasna, M., Holzer, R. and Letko V., 1993. Gravitational deformations of the Pokoradská Tabul'a Plateau *Seventh International Conference and Field Workshop on Landslides.* S. Novosad & P. Wagner (editors). A.A.Balkema, Rotterdam-Brookfield.

Janova, V., Kovacik. M., Liscak, P., Ondrasik, M., Kovacikova, M, Lubomir, P., Spisak, Z. 1994. Assessing the engineering geological factors of the environment in Slovakia. *Acta Geologica Hungarica.* Vol. 37. No 1. 119-134. Budapest.

Kovacik, M. 1992. Slope deformations in the flysch strata of the West Carpathians. In Landslides, Bell (editor). *Proceedings of the Sixth International Symposium, International Association of Engineering Geology.* D.H.Bell (editor). 10-14 February, Christchurch, New Zealand. A.A. Balkema, Rotterdam-Brookfield.

Kovacik, M. 1999. An overview of slope failures in regions of Western Carpathians. Programme for Landslide workshop, *DFID Landslide Implementation Strategy Project and NATO-funded research. Geological Survey of Slovak Republic (GSSR), Bratislava, Slovakia.*

Kovacik, M. and Paudits, P. *1998.* Map of the relative susceptibility to mass movements in the Tatras region, Slovakia. *Proceedings of the Eighth International Congress of the International Association of Engineering Geology and the Environment.* D. Moore and O. Hungr (editors). 21-25 September, Vancouver, Canada. A.A.Balkema, Rotterdam-Brookfield.

Kovacik, M. and Suchankova, Z. 1993. Systematic inventory of slope deformations in the Slovak Republic; its use and possibilities. *Seventh International Conference and Field Workshop on Landslides.* S. Novosad & P. Wagner (editors). A.A.Balkema, Rotterdam-Brookfield.

Kovacikova, M., Kovacik, M. and Modlitba, I. 1989. Earthflow in Kliestina village cadaster. *Geologicke prace, Spravy* 88. pp. 177-199. GUSD, Bratislava.

Malgot, J. and Baliak, F. 1993. Influence of landslides on the environment in Slovakia. *Seventh International Conference and Field Workshop on Landslides.* S. Novosad & P. Wagner (editors). A.A.Balkema, Rotterdam-Brookfield.

Marsh, S. H. 2000. Landslide hazard mapping: summary report. *British Geological Survey Technical Report* WC/00/11.

Nemcok A. and Mahr, T. 1974. Kamenne ladovce v Tatrach. (Rock glaciers in the Tatras Mountains). *Geograficky casopis.* 4: 359-373.

O'Connor, E. A. 1999. Report on a visit to Slovakia, 7 – 18 June, 1999 *BGS Technical Report* WO/99/20R. British Geological Survey, Keyworth.

Northmore, K. J., Ahmed, R., O'Connor, E. A., Greenbaum, D., Macdonald, A. J. W., Jordan, C. J., Marchant, A. P., and Marsh, S. H. 2000. Landslide hazard mapping: Jamaica case study. *British Geological Survey Technical Report* WC/00/10.

Vlcko, J., Baliak, F. and Malgot, J. 1993. The influence of slope movements on Spis Castle stability. *Seventh International Conference and Field Workshop on Landslides.* S. Novosad & P. Wagner (editors). A.A.Balkema, Rotterdam-Brookfield.

Vlcko, J., Wagner, P. and Mika, R. 1996. The destruction of the Skalka Monastery as a result of deep-seated deformations. In *Landslides*, Chacon, Ingaray and Fernandez (eds). Balkema, Rotterdam.