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Landslide modelling for natural risk/hazard assessment with GIS

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ABSTRACT

Catastrophic geomorphological processes occurring in the landscape are a manifestation of its topographical attributes. Spatially variable topographically based attributes permit the distribution of geomorphological phenomena to be mapped in the landscape. They can be derived from digital elevation models using a variety of surface analysis methods and spatially modeled. In addition, the integration of geomorphological data in GIS demands extensive consideration of GIS data models and analytical techniques.

Key words: landslide modelling, GIS

1. Introduction

Maps have been the principal medium for the summary and representation of hazards posed by natural processes (e.g. Varnes, D.J., 1984). Such maps typically present hazards as high, medium or low ordinal risk zones, as values of probability of occurrence for individual cells, or as a dimensionless ratio summarizing a physical state.

The geographic information system (GIS) has an important role to play in hazard assessment because of the following advantages over traditional methods:

1. Spatial modelling and map creation can be done on the same computer,
2. A variety of models can be created and displayed to reflect different hazard scenarios and in forms other than the traditional map,
3. The implications of hazards in terms of risk and planning can be made understandable to planners.

GIS is an organised collection of computer hardware, software, geographical data and personnel designed to efficiently capture, store, update, manipulate, analyse and display all forms of geographically referenced information (Voženílek 1998).

2. Modelling with GIS

Spatial modelling in GIS environment serves the two following related purposes (Chou 1997):

1. Spatial models analyse phenomena by identifying explanatory variables that are significant to the distribution of the phenomenon and providing information about the relative weight of each variable.
2. Spatial models are most useful for predicting the probable impact of a potential change in control factors. In other words, spatial models can be used to estimate the results if the values of selected variables are altered.

Natural hazards are the results of a subset of processes that affect the surface of the Earth that are perceived as threats to society. Ideally, we should be able to identify the process responsible for the hazard, devise an appropriate mathematical representation of the process, and use this to provide a computer simulation of the hazard over the area of interest. In practice, this deterministic approach may not be readily applied because:

1. The hazard may be created by a combination of coupled processes,
2. The processes may be too poorly understood to be represented by a physical model,
3. Simulation may be too time consuming,
4. Information on physical variables may not be available.

An alternative way to model natural hazards is to use spatial and/or temporal characteristics of previous hazard events to infer the ambient hazardous states of a number of environmental variables and forecast the liability of hazards in the future. The problems with an empirical approach are that:

1. The variables available for measurement may not have the same values as those obtaining during the hazard event,
2. The choice of which environmental variables to use is largely guesswork, and the model may only explain a fraction of the hazard variance,
3. Cross-tabulation ignores potentially useful information in the spatial autocorrelation of the data.

Both of these modelling approaches can be implemented within a GIS. The empirical or inductive approach is one that fits most closely with the analytical capabilities of a vector GIS and his most employed in hazard analysis. The deterministic or deductive approach is more usually associated with simulation modelling in standalone computer programs rather than as a component of a GIS.

3. Landslide modelling

Catastrophic slope processes of earth mass are frequent phenomena in flysh rock regions of the Western Carpathians in the east of the Czech Republic. They cause large amounts of damage to agriculture, gardening, communications and constructions, and they are an important factor of landscape design. Landslides are an important landscape problem in the Carpathian part of the Czech Republic. In order to establish which slopes are most at risk, their spatial incidence can be modelled using geographical information systems techniques together with a database describing past landslides.

The occurrence of large landslides often corresponds to a high number of depression and erosion grooves on the slopes. During high precipitation events these grooves are filled by water and saturate the surrounding material. This saturation is the most frequent cause of landslide occurrence in flysh rocks. There are places where landslides occur after rainfalls, which weaken the stability of flysh beds.

There are several approaches of how to assess the landscape in terms of landslide occurrence. One of the most powerful ways is the modelling of landslide occurrence by GIS techniques. This approach involves many scientific topics and brings essential knowledge for decision making about landscape planning into practice.

The basic data input for modelling was a large dataset of previous landslides, geomorphological knowledge of landslides as slope processes and basic topological information from topographical maps collected in GIS. The presented model can be used either in many regions or in modelling other spatial phenomena.

4. Landslide database

Field investigation of landslides and other slope deformations in the Trkmanka catchment was carried out by many institutions. Information and experience obtained are collected in a large database in Geofond of Czech Republic in Prague called the “Register of slope deformations“. A map of the slope deformation drawn on the background of a topographical map is one part of the register. Information from the register describes details of location and parameters for each registered landslide. They are organised in the database according to the items in Table 1.

Figure 1: Trkmanka Catchment – the area under investigation.

Table 1: Register of slope deformations - description of structure

REGISTER of slope DEFORMAtions

identification data:

number, location, district, index number of sheet of Basic topographic map, index number of Military topographic map, level of investigation, classification, age, shape of deformation, recent activity, area, thickness,

numeric and descriptive data:

x - co-ordinate, y - co-ordinate, z - co-ordinate, method of slope angle measurement, slope angle, elevation range, length, width, aspect, origin, documentation, revision date,

natural conditions (1):

land use, taxonomy unit, stratigraphical background, geological structure of slope,

natural conditions (2) and stabilisation:

conditions of surface, relationship to stream network, springs, cause, destroyed and endangered features, stabilisation, year of stabilisation,

detailed description of deformation:

morphology of surface, intensity of slope failure, cracking, slip surface, backwall of slip, shape of slip backwall, height of slip backwall, margins of deformation, toe of deformation, height of toe,

compiler, institution, revision:

compiler, institution, complementation, revision.

The register involves data on existing landslides. There are more than 100 records available including items on morphology and the location of landslides in the catchment and its surroundings. These data were used for the defining of factors which are highly linked with slopes liable to landslides. The factors are then used in completing and calibrating computer models.

Due to the relative complexity of relief landslides occur in the whole range of surfaces except flat plains. They do not occur on any particular type of relief. Aspect is not the most relevant factor other than there is a higher frequency of landslides on the northern, northwestern and southwestern slopes. Slope angle is one of the most important factors. More than 95 % all landslides occur on slopes with angles 15–45°. Lithology of the slope bedrock is also an import factor. The most frequent landslide occurrence is linked to flysh rocks and loess. Further, the thicker flysh and loess beds are more liable to sliding than thin beds. There are many causes of landsliding but climatic factors are the main cause of 98 % landslides in the Trkmanka catchment. Lower influence can be defined for marginal erosion of water streams and for anthropogenic impacts, mainly slope undercutting. Earthquakes can be eliminated as a cause of sliding in the catchment. In addition, it is clear that valley slopes and margins of gullies can be undercut easily.

5. Geomorphological background

Whatever the causes, they are always connected with changes of water volume in deposits or with earthquakes. In addition, the long-term slope stability of flysh rocks is determined by the morphology of the relief. The flysh rocks are a typical example of rocks which are highly liable to slide. The flysh is a thick formation composed from slightly lithologically different beds. It often consists of clays, sands, claystones, sandstones, conglomerates, marls or limestones. The rock types are ordered in sequences separated by disconnected cracks of sedimentation or denudation. Loess is a material of eolic origin. It consists of very fine quarcit dust of element size from 0.001 to 0.05 mm. The bigger fragments (several mm) occur locally in loess of hilly lands in the Czech Republic – in the Trkmanka catchment, too. Loess has a non-bed structure and column decay. It is are of Pleistocene age. There are differences in the behaviour of loess and flysh rocks; this depends also on their thickness and the occurrence of cracks.

The register of slope deformations and project spatial databases were used to complete a set of data layers describing the catchment, i.e. land use, slope angles, lithology etc. Only available data were used to model landslide risk. Land use was assessed using of topographic maps, field investigation and aerial photo processing. The layers of slopes and aspects were derived from the digital elevation model as a result of surface analysis. Slopes are expressed in degree, aspect in degree of azimuth and then classified in an 8-part wind rose. Lithology was digitised from different sources (partial studies, geological maps etc.) because of the lack of a complex geological map of the catchment.

6. Models of landslide risk/hazard assessment

Modelling is important method for the studying of many topics in physical geography. Modelling allows the use of mathematical expressions to represent the behaviour of particular geographical systems. There are many different models used in physical geography. Models should not be too complicated in order to be useful for investigation, or too difficult to apply. Models must not be a duplicate but also should not be too simple in order to make modelled phenomena less important.

Table 2: Coding of categorical data for modelling

Factors	Codes	Values
Slope angle	1	0 – 2°
	2	2 – 15°
	3	15° and more
Lithology	1	fluvial sediments
	2	Neogene sands, flysh sandstones, claystones and conglomerates
	3	loess and clay
Aspect	1	South-east – S, SE, E, NE and plains
	2	North-west – N, NW, W, SW

Available information and basic knowledge of landslides have been applied in the process of model creation and defining of places with the highest landslide risk. All created models are very powerful tools for describing and assess not only landslides but also other natural phenomena. Modelling has performed according to general regulations and brought adequate results. Three fundamental methods of modelling and results have been developed – nominal, ordinal and categorical models.

Nominal models represent the simplest type of models. Its nature is in defining relationships between elements using logical operations of Boolean algebra. Due to its simplicity they are easily applicable in the GIS environment. There is a procedural equivalent in GIS – operation "sieve mapping" Modelling method sieve mapping is one of the most typical GIS operations. Despite it having several disadvantages it is very popular. Mainly it is too generalised in factors involved in the model and the defined categories are too comprehensive.

Ordinal model (modelling by weighting factors) is an advanced approach to improve the modelled risk/hazard. Each input factor in the model is expressed in a map layer by a simple ordinal scale according to its importance for landsliding. The scales have a certain weight regarding the model factor. The metric chosen is some arbitrary score for each category on an assumed underlying scale of susceptibility. The relative incidence of past landslides was converted into a risk index by taking the ratio of their incidence in each category of each factor divided by the average incidence over all categories of the factor concerned. These individual factor risk indices were then assigned to classes on an ordinal scale (low = 0, medium = 1, high = 2) and these summed to give an overall risk measure. The coverages used were: aspect, slope, lithology and land use. The final measure of model had a range 0–8.

The highest level of developed model is the categorical model. Using Bayesian probability theory makes it possible to convert expert knowledge and experience into a probability scale. However it has several disadvantages. It cannot distinguish which layers are relevant for landsliding, which are minor and which of them can be accepted as unimportant or even ignored. It also cannot model interactions between factors internal and external to the model. Modelling by continuous functions is another common research approach. Some authors (i.e. Luzi, Fabbri 1995) have investigated its implementation in landslide modelling. The most suitable approximation of continuous models for landslide modelling based on available layers is a categorical model. The categorical model uses available factors and data on their information levels. It uses model factors as phenomena represented by at least ordinal and, ideally, interval or ratio data.

Regression analysis is often used for the calibration of categorical models. It combines landslide probability and each category of input factors. The presented approach is based on the analysis of ordinal data. The model was created for the calibration of a continuous function of the form:

P (landslide) = f (slope angle, lithology, aspect),

where independent variables are on the right side of the equation and are used as coded categories of input factors and represented by ordinal digital data. This approach involves using data from the landslide database of GEOFOND CR, which gives the best conditions for defining landslide risk. The model calibration cannot use linear regression of the smallest squares for two reasons. Firstly, the dependent variable "landslide occurrence" is binary (0/1, landslide / no landslide). Secondly, the independent variable "lithology" is expressed by an internal ordinal (categorical) variable. Special software products, i.e. GLIM or ECTA, often perform estimations of model parameters.

Data about landslides were reorganised into three ordinal variables for the needs of this modelling. The study objective was to create a model, using slope angle, lithology and aspect as independent variables, which describes existing landslides as accurately as possible.

In the model, one dependent variable (landslide) and three independent variables were available. The number of possible models, which can be used, is not too high. The basis of this assessment was the analysis of existing landslides and the expert assessment of the influence of each factor on the landslide risk. The model was expressed by an equation of continuous function:

$$P = f(x,y,z) \quad (1)$$

where x, y, z are dependent variables representing slope angle (x), lithology (y) and aspect (z). Based on relationships and fundament of factors and their type of digital data, the function was defined by linear equation with constants representing importance of factors for landsliding. At the beginning of modelling the constants are used as letters and then by calibration (solution of linear equation set and regression relationships) they are

Table 3: Categorical modelling – parameters and model results

Slope characteristics			*Model results*		
Slope	Lithology	Aspect	Observed	Probability	Model estimation
0–2°	Loess and clay	NW	2	0.017	0.348
2–15°	Loess and clay	NW	14	0.120	0.499
15° and more	Loess and clay	NW	35	0.299	0.650
0–2°	Neogene sands, flysh sandstones, claystones, conglomerates	NW	1	0.009	0.283
2–15°	Neogene sands, flysh sandstones, claystones, conglomerates	NW	12	0.103	0.334
15° and more	Neogene sands, flysh sandstones, claystones, conglomerates	NW	20	0.171	0.485
0–2°	Fluvial sediments	NW	0	0	0.018
2–15°	Fluvial sediments	NW	0	0	0.169
15° and more	Fluvial sediments	NW	0	0	0.320
0–2°	Loess and clay	SE	1	0.009	0.330
2–15°	Loess and clay	SE	13	0.111	0.481
15° and more	Loess and clay	SE	11	0.094	0.632
0–2°	Neogene sands, flysh sandstones, claystones, conglomerates	SE	0	0	0.165
2–15°	Neogene sands, flysh sandstones, claystones, conglomerates	SE	2	0.018	0.316
15° and more	Neogene sands, flysh sandstones, claystones, conglomerates	SE	6	0.051	0.467
0–2°	Fluvial sediments	SE	0	0	0
2–15°	Fluvial sediments	SE	0	0	0.151
15° and more	Fluvial sediments	SE	0	0	0.302

given a numerical value (either absolute or weighted – a centre of interval). Then the model equation has the form:

$$P = 0{,}151x + 0{,}165y + 0{,}018z. \quad (2)$$

Results of modelling correspond to qualitative geomorphological knowledge about landslides in that part of the Carpathians. They can be used to reach an unbiased strategy by polygon overlay. Figure 2 shows the results of this modelling method in the studied area. The results represent the modeled estimation of landslide on slopes (item Model estimation in Table 3). Probability from 0 to 0.299 delimits slopes with low landslide risk; probability from 0.3 to 0.599 delimits slopes with moderate landslide risk and probability more than 0.6 delimits slopes with high landslide risk. The map in Figure 2 shows the modeled results – slope delimitation of landslide risk.

Table 3 shows all possible combinations of ordinal data for slope angle lithology and aspect. However, they all do not occur in the catchment (for example fluvial sediments on slopes 15° and more). For all combinations, the occurrence of probability is computed, some of which do not exist in reality.

The results of the modelling must be accepted critically. There are more partial factors influencing landsliding than mentioned above. Although the categorical model reflects landsliding well, it is only general approximation of landslide distribution as a natural spatial phenomena. Some important factors (i.e. slope undercutting, slope length, thickness of sediment layers, type of cultivation etc.) are missing in the model.

7. The impact of landslidies on human activities

There is no doubt that increasing the believability and honesty of GIS products will increase their utility for decision-makers. However, developing a close fit between map analysis and policy goals is of such critical importance that it requires a considerable level of effort and foresight on the part of the analysts and mapmakers, to be made. When the maps fail to have an impact, it often has little to due with model nuances or data gaps, but more with a lack of fit between cartography and decision reality.

An important part of analytical or modelling studies is an assessment of the impact of natural hazards on human activities. Despite a high risk of landsliding in the Trkmanka catchment there is high density of various human activities – built-up areas, railways, roads, fields of arable land etc. Elements of all activities potentially impacted by landsliding are summarised in Table 4 and shown in Figure 2.

Table 4: Human activities under landslide risk

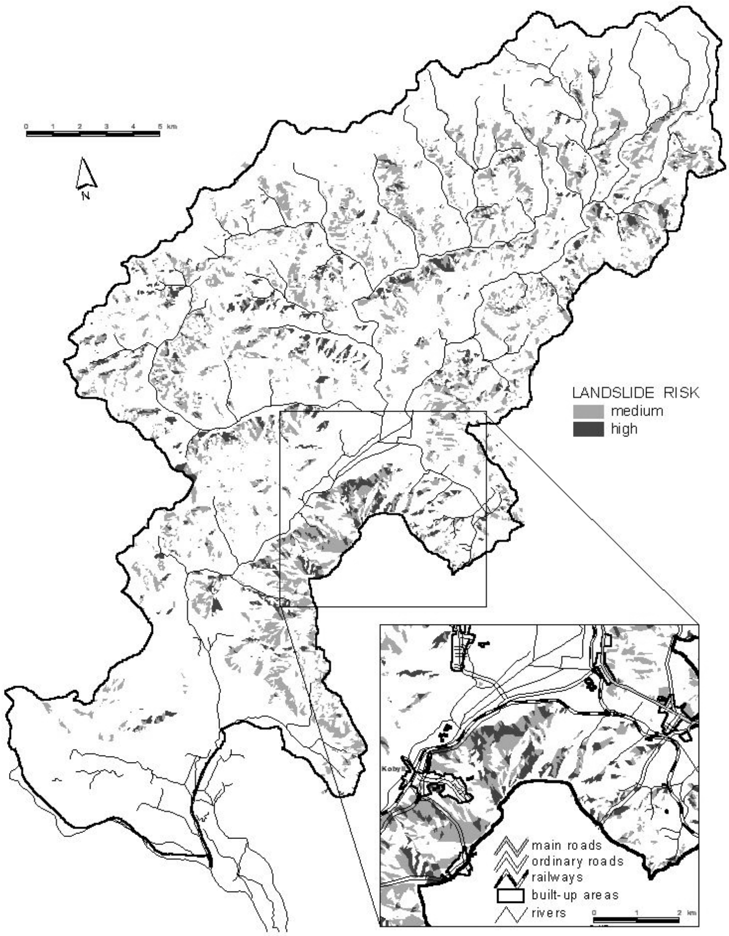
Length of railways under landslide risk (in metres)		
Medium	1 234	
High	1 199	
Built-up areas under landslide risk (v ha)		
Medium	66.9117	
High	3.6088	
Length of roads under landslide risk (in metres):		
	Main roads	*Ordinary roads*
Medium	2 821	17 774
High	1 011	4 304
Areas of risk zones located in woods (in ha)		
Medium	329.9948	
High	44.9596	

8. Further advanced research

Although some theoretical models can provide a basis for predicting how far ahead of the advancing front the effects of the surcharge may be felt, it has several principal shortcomings. One is the assumed symmetry of the loading about the contour axis. This symmetry does not exist in landslides. The second can be the assumption of vertical loading only. Shear tractions will be produced where the active slide overrides the inactive slide. Improved models should be developed to address these problems.

For further research a Global Positioning System survey can be initiated to determine if satellite geodesy can rapidly map the slide velocity field, describe the spatial and temporal distribution of velocity, and determine whether the inactive slide is moving relative to a stable benchmark well away from the slide.

Figure 2: Results of categorical modelling of land-sliding and their impact to human activities.



9. Conclusion

There are more methods for landslide modelling than the above presented in the Trkmanka catchment. The GIS environment is a very advantageous one in which to perform modelling. GIS allows one to prepare input data carefully, perform modelling and obtain cartographic visualisation of the results. A high degree of attention must be given to different information levels of input data reflecting modelled phenomena. According to the types of input – nominal, ordinal, interval and ratio – the model must be built on the same information level because the results are of the same level. Types of digital data and its information level cannot be confused or mixed.

More statistical methods can be used to derive global functions for hazard potential mapping in a GIS. At its simplest, this approach involves calculating the number of point hazard events per unit area for each polygon and for each category of independent variables (e.g. Gupta, Joshi 1990). More input factors can be involved in the modelling (e.g. in a study Wadge, Wislocki, Pearson 1996).

It is clear that any list of GIS functionality required to model even a restricted set of natural hazards would be very long. In any GIS used to assess more than one hazard, a variety of spatial analytical functions will be required, not all of which will be available in the best GIS. There is a need to make earth scientists aware of the forms in which the planners can best understand and use the information present in a risk/hazard map. There are the design requirements of a GIS for natural hazard assessment: comprehensive spatial analytical functionality; interfaces to external software; and user-friendly systems that can be easily manipulated by the interested parties.

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MODELOVÁNÍ SESUVŮ PRO STANOVENÍ PŘÍRODNÍCH OHROŽENÍ V GIS

Résumé

Katastrofické geomorfologické procesy se v projevují topografickými atributy, které umožňují mapování geomorfologických rysů krajiny. Tyto rysy mohou být určeny z digitálních výškových modelů různými analytickými metodami povrchu a prostorově modelovány. Integrace geomorfologických údajů do GIS vyžaduje rozsáhlou přípravu datových GIS modelů a analytických technik.

V oblasti flyšových hornin Západních Karpat na východě České republiky je častý výskyt katastrofických svahových procesů. Pro určování, které svahy jsou nejvíce rizikové, může být modelováno prostorové rozšíření sesuvů využitím technik GIS a databáze zahrnující dosavadní sesuvy. Základními vstupními údaji pro modelování situace v povodí Trkmanky byla tato databáze a topografické mapy v GIS, dále terénní pozorování a zpracování leteckých snímků. Byl zpracován model pro kalibraci funkce P (sesuv) = f (sklon svahu, litologie a orientace svahu), jehož výsledky pravděpodobnosti rizika sesuvů na svazích (obr. 2, tab. 3) odpovídají kvalitativním geomorfologickým poznatkům o této části Karpat. Podstatnou částí analytických a modelových studií je také hodnocení vlivu přírodních ohrožení na činnost člověka (obr. 2, tab. 4).

Existuje řada dalších metod pro modelování sesuvů, přičemž prostředí GIS umožňuje jak vhodné zpracování vstupních dat, tak provádění a kartografickou vizualizaci výsledků modelování.