Rockfall hazard: a geomorphologic application of neighbourhood analysis with ILWIS

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ABSTRACT

As a test for the implementation of neighbourhood analysis functions within ILWIS, a program was developed dealing with neighbourhood analysis for one specific problem: the calculation of the velocities of rolling blocks from rockfall-producing slopes. The pixels with maximum height differences within calculation windows were selected from a DTM and data from the same locations in other maps were used to calculate the velocity in a number of iterations. The program can be used for rockfall hazard mapping on general scales.

The development of techniques for the analysis of geographic data with the help of geographic information systems has been very rapid during the last decade. With the availability of PC-based, low- cost and—at the same time—powerful GIS packages such as ILWIS, the standard data gathering and data analysis techniques for most earth science applications have needed to be reviewed and adapted to use within a GIS. Using a GIS opens possibilities in analysis that were unthinkable before, since both spatial and non-spatial relationships can be used in rapid calculations.

In geomorphology, the potential use of GISs for modelling processes such as mass movements is also large [11]. A restriction in the use of the existing raster map calculation programs, however, is that they can do only row- and column-fixed map overlays and calculations. With a few exceptions, it is possible to use only pixels with the same row and column numbers in different maps. For most geographic applications, this is a serious limitation, since many variables are spatially related to each other.

In this article, some results are presented of the development of a preliminary neighbourhood analysis program, dealing with only one type of problem: the calculation of the velocities and run-out distances of rockfall debris.

NEIGHBOURHOOD ANALYSIS

In general, neighbourhood analysis is used for interpolation techniques, to calculate distances, compute slope angles and aspects, or to calculate statistical values of a map. Many applications of neighbourhood analysis require a description of the topology of a map [3]. From this point of view, it would be best to develop a neighbourhood analysis program that uses vector data. These data, however, should be used in conjunction with maps derived from interpolation programs (such as a DTM) or remote sensing data that are in the form of raster maps. The neighbourhood analysis program was therefore made for the raster domain.

There are already two types of programs within ILWIS that can perform some kind of neighbourhood analysis:

- the filtering program in the remote sensing module is used (among other things) to enhance images and to calculate gradients and aspects from a DTM
- the "distance" program generates a raster image in which each pixel represents the distance to the nearest of a set of target pixels [5].

Both types of neighbourhood analysis are rather rigid: they can be applied to only one map at a time. Furthermore, it is not possible to use them simultaneously with the standard map calculation ("Mapcalc") commands.

The program for neighbourhood analysis that was developed in this study was based on the algorithm of the distance program. Some characteristics of this algorithm are:

- the program uses a source map on which the pixels are indicated that serve as a source for a given process. Another map is used to define the relationships between the pixels (in this instance a DTM). Further maps can be used containing necessary input parameters for the calculation
- for every pixel, a 3 x 3 window is defined so that only the eight neighbours and the pixel value itself are taken into account when recalculating the new value (see Figure 1)
- for each iteration, the maximum difference between the central pixel and one of the eight neighbours

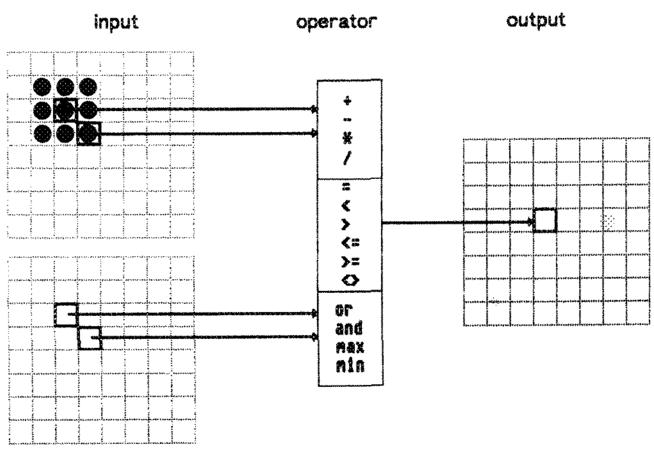

FIGURE 1 Neighbourhood anaylis: window, operations and functions

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- a calculation is made on the new value of the central pixel relative to the neighbouring pixel, with the highest difference using the standard operators of the map calculation program. The new value is stored in the resulting map (see Figure 2)

- the window moves one pixel and the process is repeated. The resulting map is calculated in a number of iterations with the window moving either upward or downward along the lines of the map until there are no more changes.

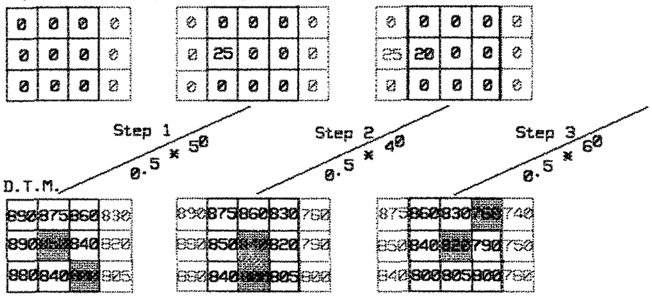

FIGURE 2 Simple example of neighbourhood analysis
The relationships between the central cell and eight neighbours are evaluated. The maximum height difference divided by two is stored in the output map. The pixels with the maximum height difference are shown in grey tones. In this very simple example, no iterations are necessary and no other input images are used in the calculation. Distances between pixel centres were not used. In the rockfall program itself, however, these factors were taken into account

THE STUDY AREA

All maps used to test the program came from a methodologic study of natural hazard assessment in the Hintere Bregenzerwald area, in the province of Vorarlberg (Austria) [8]. The map scale was 1:10000. The area is characterized by many oversteepened and unstable slopes resulting from the combination of severe glacial erosion during the last glaciation and the presence of rock materials that are very susceptible to mass movements (especially the so-called flysch formations are very heterogeneous with respect to lithologies and geotechnical properties).

The elevation within the area varies between 700 and 2400 m asl. Rockfall is one of the most prominent mass movement processes occurring in this area. The present extent of the rockfall debris was mapped in detail on 1:10000 geomorphologic maps.

ROCKFALL HAZARD ASSESSMENT

Rockfall hazard can be assessed in a number of ways. Jahn [6] developed empirical equations developed from experiments with falling rock blocks. Kienholz [7] used field evidence of old rockfall debris for hazard zonation. Among others, Bozzolo, *et al* [2] and Spang and Rautenstrauch [10] developed complicated computer programs that calculate in detail the path of a rockfall block along a profile line, taking into account the various ways of moving (falling, rolling, sliding and bouncing).

A general and simple method for defining the run-out distance for falling blocks was developed by Scheidegger [9]. With this method, the velocity of a rolling spherical block is calculated along a profile line that is divided into a number of triangles (see Figure 3). The energy condition of a block at point A is described as follows:

$$E_{kin} + E_{pot} = \tfrac{1}{2} \times m \times V_A^2 + m \times g \times h_A \qquad [1]$$

When the rock has reached point B, the following holds:

$$E_{kin} + E_{fric} = \tfrac{1}{2} \times m \times V_B^2 + \mu \times m \times g \times \cos\beta_A \times S_A \qquad [2]$$

where:

E_{kin} = kinetic energy
E_{pot} = potential energy
E_{fric} = frictional energy
V_A = velocity at point A
V_B = velocity at point B
m = mass of the block
g = gravitational constant (9.81 m/s^2)
h_A = height difference between A and B (in m)
μ = friction coefficient
β_A = slope angle
S_A = length of the slope between A and B (in m)

In equilibrium, *[1]* and *[2]* must be equal, and the following equation results:

$$V_B^2 = V_A^2 + 2 \times g(h - \mu \times D) \qquad [3]$$

where D is the horizontal distance between A and B ($D = \cos\beta_A \times S_A$). For the next triangle, a similar equation can be used in which the velocity at C relates to that in B. Equation *[3]* reflects the spatial character of the velocity, *ie*, the velocity at point B depends on the velocity at its neighbouring point A when A has a higher elevation and is located between B and a rockfall source area. This method is suitable for application on a general scale, where the input maps show limited detail. The velocities of blocks originating from given source areas can be calculated and displayed in a map. Variables h (height difference between two adjacent pixels) and D (straight or diagonal dimension of a pixel) can both be obtained from a DTM. The friction coefficient is obtained from the engineering geologic map. The area between the rockfall source and the point at which the velocity is 0

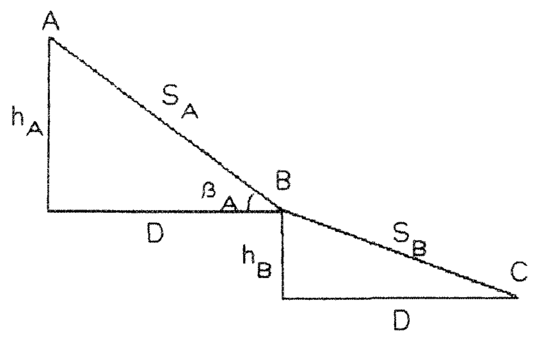

FIGURE 3 A slope as a series of triangles for calculating velocity of a rolling spherical block

(which is the "run-out" distance from the source) is considered to be the potential rockfall-endangered zone.

INPUT DATA

For the calculation of rockfall velocities, the following input maps were used:

(1) Digital terrain model (DTM) derived from a 1:25000 scale contour map of the area with a contour interval of 20 m. This map was digitized and the ILWIS contour interpolation program was used to produce a DTM.

(2) Rockfall source area map obtained by

- extracting all slopes steeper than 60 degrees (from a slope map)
- renumbering the digitized geomorphologic map in which "rockfall producing slopes" were mapped as a separate legend unit

(3) Friction coefficient map: for non-cohesive soils, the tangent of the angle in which rockfall debris is found in nature is an indication of the friction coefficient [9]. These values were obtained by renumbering the digitized engineering geologic map with attribute data derived from field measurements (see Table 1).

TABLE 1 Friction coefficents used in mapping (*= estimated values)

Material	*Friction coefficients (μ)*
Tills (*)	0.35 - 0.5
Residual soils (*)	0.4 - 0.5
Fluvial materials (*)	0.4 - 0.5
Bare rock:	0.4 - 0.9
Scree materials:	
- marl	0.35 - 0.45
- flysch	0.6 - 0.7
- sandstone	0.7 - 0.8
- dolomite	0.7 - 0.8
- limestone	0.8 - 0.9
Rockfall materials	0.9 - 1.0
Effect of vegetation:	
- open forest (*)	1.0 - 2.0
- dense forest (*)	> 2.0

(4) Vegetation map: a digitized vegetation map was renumbered in three classes: dense forest, open forest and non-forested areas. It was assumed that dense forest acts as an almost complete barrier to small rockfalls. The effect of the vegetation was incorporated in the friction coefficient map by increasing the coefficient in such a way that the run-out distances were in accordance with the empirical values given by Jahn [6].

The input data are schematically represented in Figure 4. The dotted line between the vegetation map and the friction coefficient map indicates that the former map is not essential as an input map for the program.

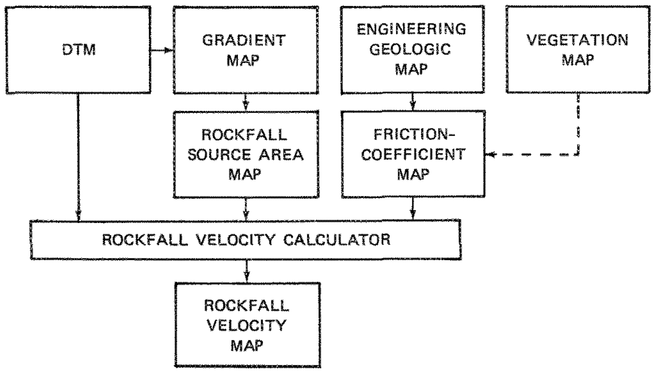

FIGURE 4 Schematic overview of the rockfall hazard analysis

RESULTS

While the rockfall velocity computer program is running, the gradient map is transferred into a rockfall velocity map in which the classified velocities are displayed in grey tones. In the rest of the area a classified DTM is displayed in alternating grey tones to give an impression of the topography. Figures 5A, 5B and 5C show the calculated rockfall with and without the effects of vegetation included in the input. One of the most striking features on these maps is the occurrence of more or less concentric areas with equal velocities radiating from the source areas. Some source areas have only a very limited accompanying accumulation area because of topographic conditions (*eg*, steep slopes bordering a floodplain or a circular depression) or high friction values of the material underlying a rock scarp.

Several other output maps were made with the rockfall velocity program, using slightly different input maps, such as:

- a rockfall source area map derived from the geomorphologic map (see Figure 5C). In this map, the areas with velocities > 0 were larger than in the first maps because more areas were mapped as "rockfall producing" in the geomorphologic map. The result of this calculation closely resembled the extent of rockfall debris as indicated on the geomorphologic maps of the area [8]
- a constant value (0.5) as friction coefficient for the entire area, which resulted in a slightly different pattern. The extent of the rockfall-endangered area was a bit larger than in the maps with variable friction coefficients.

DISCUSSION

The accuracy of the calculated rockfall-endangered zones depends largely on the detail of the input data, and especially on that of the DTM. Unfortunately, the method used by ILWIS to generate DTMs and their derivative maps, such as gradient maps, is not as accurate as we had hoped, especially for the steeper slopes. The method of linear interpolation between digitized contour lines and the filtering technique used to obtain the first derivative of the DTM tend to "flatten out" the topography. This could be solved by incorporating breaks of slope in the process of creating the DTM [4]. A further develop-

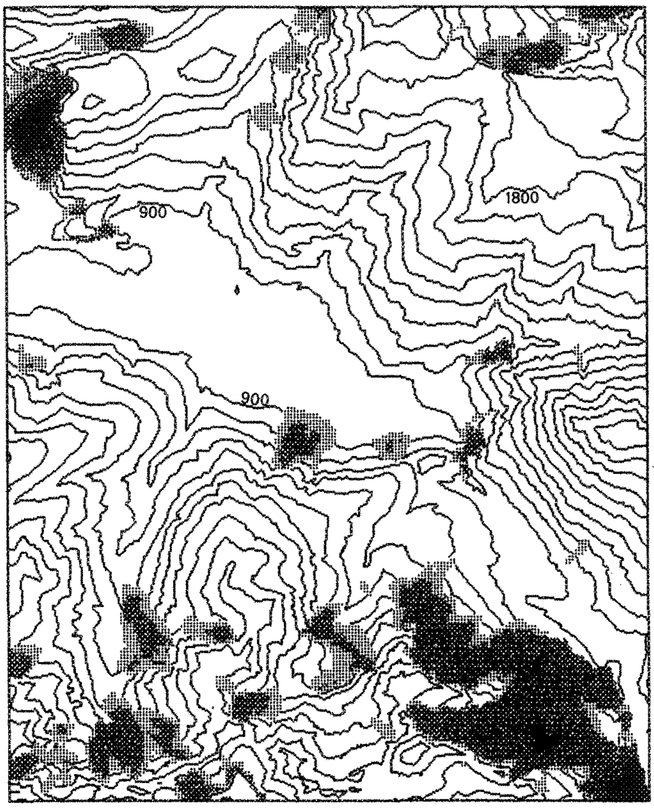

FIGURE 5A Rockfall sources derived from slope map, the effect of vegetation not included

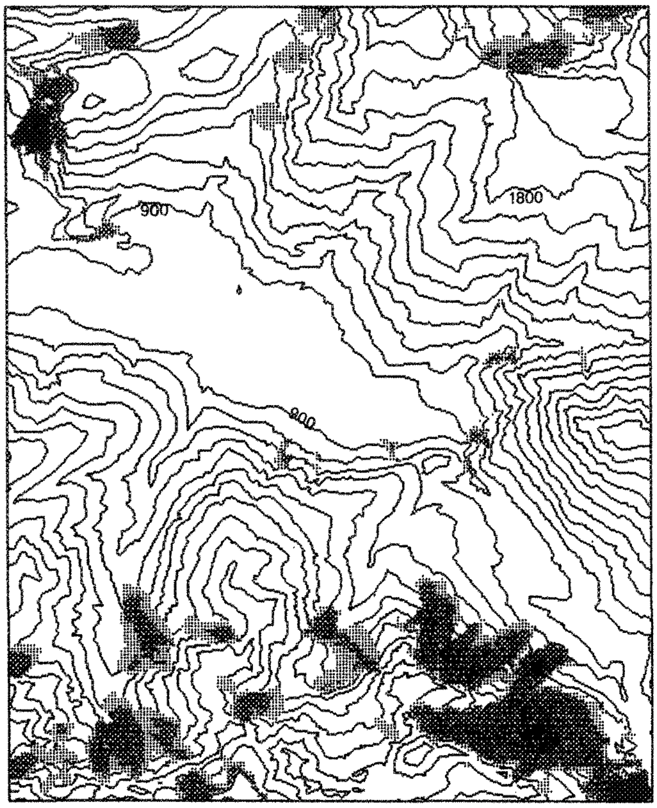

FIGURE 5B Rockfall sources derived from slope map, the effect of vegetation included

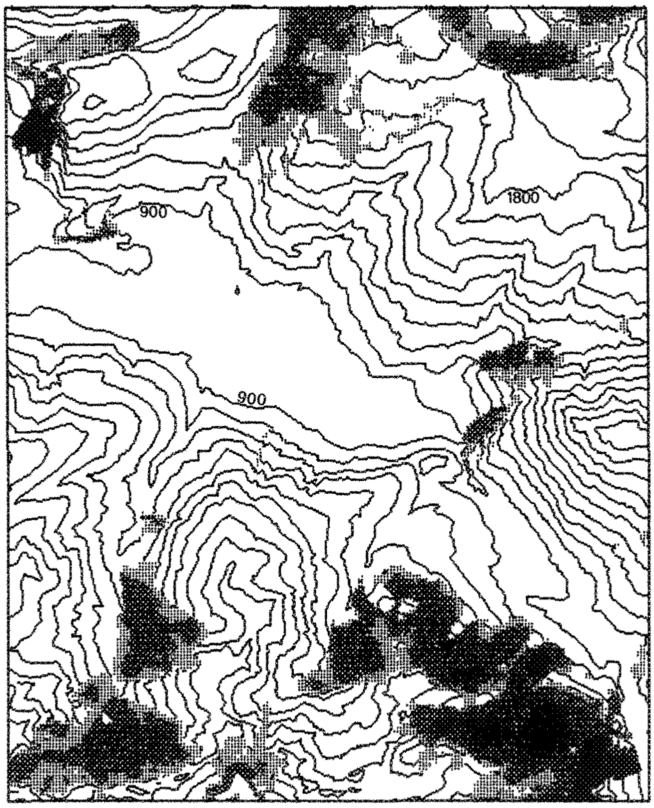

FIGURE 5C Rockfall sources derived from geomorphologic map, the effect of vegetation included

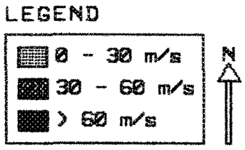

FIGURE 5 Output maps of rockfall velocity calculation program (contour interval is 100 m, pixel size is 20 m, map size is 400 x 500 pixels)

ment of the ILWIS interpolation program should remedy the problem. Using the program as it is now, the accuracy of the results could also be increased if larger-scale topographic maps were used to generate DTMs and gradient maps.

Another problem was encountered in correctly establishing potential rockfall-producing slopes. Because of the "flattening out" noted above, the extraction of these slopes from a slope gradient map could result in a reduction of the endangered areas. It is thus better to delineate these zones through detailed aerial photo interpretation on a geomorphologic map.

CONCLUSIONS

Generalized rockfall velocities can be computed for a large area using a simple neighbourhood analysis program. The algorithm that was used seems to be sufficient for the quality of the input data and provides, in a short time and with data that are fairly easy to obtain, a first insight into the occurrence of potential rockfall hazards. The program's handling of the mechanics of rockfalls could be extended by taking into account other types of movement than rolling (*ie*, falling, sliding and bouncing), but we doubt that the input data will be accurate enough for these kinds of complicated calculations.

The rockfall velocity maps produced by the program can be used as input data for studies on rockfall risk [1] if data are available on the expected sizes of the rockfall debris. The impact of a rockfall block on existing engineering structures could then be calculated. For the design of protective measures, such as rockfall galleries along roads or reinforced walls in buildings, more detailed rockfall hazard programs should be used [2, 10].

The development of the method described here was merely a first attempt to use neighbourhood analysis for geomorphologic applications of ILWIS software. In the near future, a general program for neighbourhood analysis (developed by ITC's computer department) will be implemented within the ILWIS map calculation program (Mapcalc).

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RESUME

A titre de test pour l'exécution des fonctions d'analyse de proximité à l'intérieur de ILWIS, on a développé un programme traitant de l'analyse de proximité pour un problème spécifique: le calcul de la rapidité des blocs roulants, provenant de pentes produites pas des chutes de rochers. Les pixels avec un maximum de différence d'altitude à l'intérieur de fenêtres de calcul ont été sélectionnés à partir d'un DTM et de données, des mêmes localisations tirées d'autres cartes ont été utilisées pour calculer la rapidité avec un certain nombre d'itérations. Le programme peut être utilisé pour des cartes de risques de chutes de rochers à une échelle générale.

RESUMEN

Se desarrollo un programa como una prueba para la implementacion de funciones de analisis de vecindad en el ILWIS, que se ocupa de analisis de vecindad para un problema especifico: el calculo de las velocidades de bloques rodantes derivados de pendientes producidas por caida de rocas. Los pixel con maxima diferencia de altura dentro del calculo de las ventanas fueron seleccionados de un DTM y los datos de las mismas ubicaciones en otros mapas se usaron para calcular la velocidad en un numero de repeticiones. El programa puede ser usado para el mapeo de riesgos de caida de rocas en escala general.