COMBINED METHODS FOR RISK ASSESSMENT OF MASS MOVEMENT AND EROSION SUSCEPTIBILITY IN THE ETHIOPIAN HIGHLANDS

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ABSTRACT

The Ethiopian Plateau and the Rift Valley typically display various symptoms of intensive erosion, mass movement and land degradation, which have arisen in response to rapid changes in land cover in an area of high dynamics of relief development. In order to assess the risk of these symptoms of intensive erosion and mass movement it is necessary to apply a method for the evaluation of non-linear systems. Therefore, our aim was to develop a combined method for evaluating the risk of landslides or erosion using complex system theory. This combined integrated method has been tested on two selected localities with landslide hazards on the border of the Ethiopian Highlands and the Main Ethiopian Rift. The method is suitable for a prompt risk evaluation and swift decision making.

Keywords: integrated methods; complex systems; landslides; erosion; multi-criteria analysis; Ethiopian Highlands

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1. Introduction

Nowadays, data evaluation and decision making connected with risk have to be performed under increasingly complicated circumstances. Natural risk creates very complex and dynamic systems with unstable behavior, whose description can be very complicated and more or less unreliable. That is why the evaluation and decision making processes require a combined approach, based on exact methods working with both qualitative and quantitative information as well as natural uncertainty and vagueness.

The characteristics and evolution of landforms at the zone of contact of the Ethiopian Plateau and the Rift Valley have not yet been studied in detail. This is a typical area with various symptoms of intensive erosion, mass movements and land degradation, which arose in response to rapid changes in land cover in an area of high dynamics of relief development. At the same time, infrastructure and settlements are increasingly exposed to a direct threat. In order to assess the risk of mass wasting and erosion susceptibility a combined method should be applied integrating a deterministic approach with complex system theory.

The natural non-linearity of an unstable system (i.e. an unstable slope) prevents data from being evaluated using a classic model based on linear methods because this approach may not lead to reliable conclusions (Zvelebil et al. 2006). It is also necessary to consider the fact that not all the required data are available within the requested time and spatial density. That is why it is necessary to combine classic mathematical or statistical methods of evaluating time series with tools enabling us to transform immeasurable, estimated or even approximate factors into the numerical model with the aim of evaluating and predicting features of the system after extreme changes in the conditions of certain input parameters. In this study our aim was to develop a combined method for evaluating the risk of landslides or erosion using complex system theory.

1.1 Previously used methods of evaluation in the study region

Various different approaches and methods have been used to evaluate landslide risks and erosion susceptibility on the Ethiopian Plateau. It is important to remember that not only the evaluation methods but also the availability, quality and relevance of data play an important role. Due to a lack or incompleteness of data or time series or even the non-existence of measurements, as well as the different characteristics of the sites, there are many of these sites that have not yet been evaluated or only partially or have been evaluated without a complex approach.

There are several studies describing the evaluation of the risk of landslides and erosion, where the authors present various qualitative and quantitative, as well as analytical and empirical approaches.

First example, the application of remote sensing and GIS for landslide disaster management (Ayele et al. 2014), where the natural stability of slopes is evaluated using methods for the classification of factor maps of parameters (geology, groundwater, drainage, slope, structure, aspect, etc.). Another example is the application of weights of evidence modeling for landslide susceptibility (Meten et al. 2014). This method evaluates landslide influencing factors such as slope, aspect, profile curvature, plan

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curvature, lithology, land use, distance from a lineament and distance from a water course. Weights of evidence modeling uses the Bayesian probability approach and was originally designed for the assessment of mineral potential. A study on the landslide susceptibility and causative factors evaluation of the landslide area of Debresina (Abay and Barbieri 2012) uses remote sensing and GIS for mapping and evaluating landslides. The study evaluates the landslide susceptibility based on factors such as lithology, geological structure, land use, drainage, slope gradient, slope aspect, elevation, rainfall and earthquakes. Another example is landslide hazard zonation mapping (Woldegiorgis 2008) where land hazard evaluation factors were used to characterize the landslide hazard potential in the study area, applying the limit equilibrium method. A quantitative analysis for critical slopes was also performed. Teferi (2005) carried out research on the evaluation of land degradation and landslides using an integrated GIS and remote sensing approach around the area of Sodo-Shone in Southern Ethiopia.

Ayenew and Barbieri (2004) performed landslide studies and susceptibility mapping in the Dessie area. Temesgen (2001) researched landslides in the Wondo-Genet area and evaluated occurrences of landslides and their relationships with various event controlling parameters using GIS and remote sensing techniques. A study involving a mass movement hazard assessment in Betto, Goffa district, determined that the main cause of landslide was the existence of old landslides on steep slopes that were covered by deeply weathered, closely jointed or sheared basaltic rocks (Lemmesa et al. 2000).

1.2 Model study sites

Representative sites were found within the Ethiopian Highlands and on the margin zone of the Main Ethiopian Rift (MER). Several selected sites with geohazards (especially erosion-denudation processes and mass movements) were assessed in the first step – e.g. the Andit Tid catchment area, Debre Libanos/Fiche Valley, the Dessie area, the Debre Sina area, Lake Maybar and the Melka Kunture archeological site. The two most suitable study sites were subsequently comprehensively documented through a literature search, analysis of data from DMT, satellite data and a field survey.

Two demonstrative sites in the eastern part of the Ethiopian Highlands on the border with the MER were selected for detailed analysis: 1) the Dessie graben (a hanging tectonic basin located along the western rift margin with young, high energy relief and a quantity of different types and ages of landslides and reactivations – e.g. Fubelli et al. 2008; Abebe et al. 2010; Vařilová et al. 2015) and 2) a mega-landslide area near the town of Debre Sina (a tectonically disturbed slope on the edge of the MER with a huge catastrophic landslide in 2005/2006, repeated reactivation and associated shallow debris/earth slides/flows – e.g. Alemayehu et al. 2012; Abay and Barbieri 2012; Kropáček et al. 2015).

The spatial and temporal distribution of the landslides and their typology within the study localities are mainly related to complex interactions between the local predisposed conditions and the external triggering factors. Heavy summer rainfall has been identified as the major

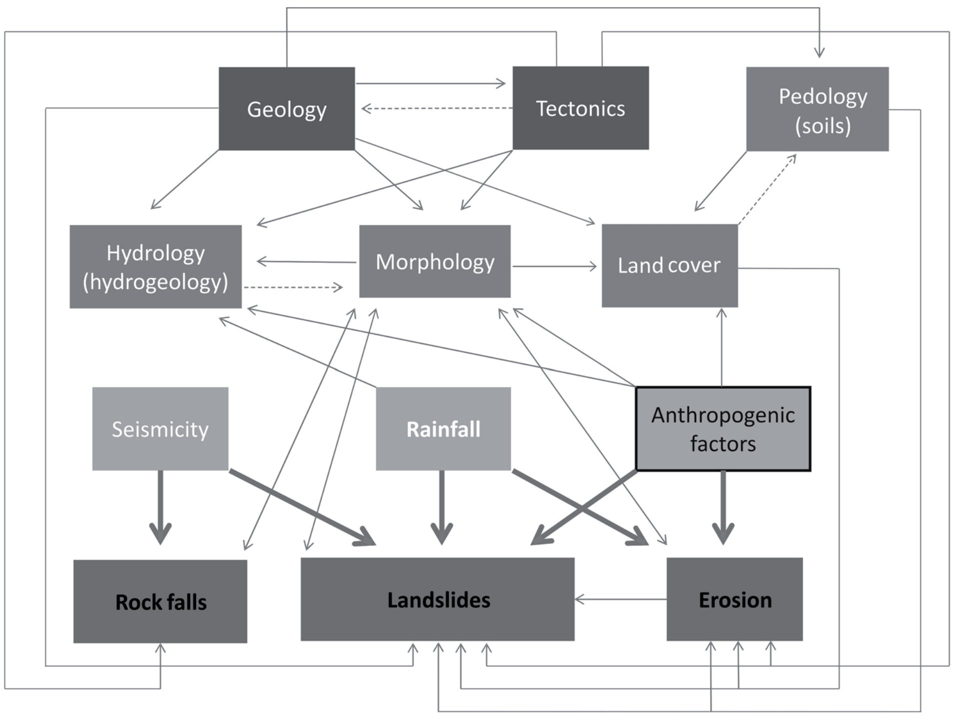

Fig. 1 Schematic representation of interactions between causative factors and consequences for studied localities.

Tab. 1 Main predisposed conditions and external factors inducing landslide activity at the Dessie graben and Debre Sina localities (assessed in a scale of several years from a common point of view); the estimation of the effect of individual influences is represent by an index number (expert estimate in per cents, separately evaluated for conditions and external factors).

Influence			Characteristic of Dessie landslides	Index (%)	Characteristic of Debre Sina landslide	Index (%)
Conditions	Relatively constant condition	**Geology** (lithology and structure, intensity of weathering, including soil characteristics)	**Tertiary volcanic terrain and its weathered products, alluvial-colluvial deposits:** Highly weathered weak basalt and vesicular basalt, un-cohesive colluvial-alluvial deposits; stratified beds – changing of more or less weak/permeable layers; abundant presence of clays and silty clays; highly plastic soils (e.g. Ayenew and Barbieri 2005)	**40**	**Tertiary volcanic terrain and its weathered products, alluvial-colluvial deposits:** Bedrock of alternating layers of basalt, rhyolitic or trachytic ignimbrites as well as tuffs (intensively fractured, highly altered and weathered) and agglomerates of different volcanic material; overlaid by basalts in the head scarp area (e.g. Abay and Barbieri 2012)	**35**
		Tectonics (faults/active faults/proximity to faults, fissures, etc.)	**Tectonic depression along the Main Ethiopian Rift margin:** major parallel faults running in a N–S direction limit the Dessie Graben, locally crossing of faults (sets of E–W trending faults), slow descent of valley along both faults, highly jointed basalt basement	**15**	**Main Ethiopian Rift escarpment with extensional regime:** major morpholineaments striking SSW–NNE related to the African Rift; several minor morpholineaments striking NE–SW, NW–SE, E–W, and N–S are dissected by the major ones (probably of older age)	**35**
	Changing condition (by self-development and by external influences)	**Hydrology regime, hydrogeology** (aquifers and aquitards, system of drainage, etc.)	Fast drainage of infiltrated water by steep slopes and numerous tectonic lines together with a lateral movement of groundwater due to the existence of layers of impermeable rock and interbedded paleosoils, which also prevent deeper infiltration; low storage capacity; higher stream density (Ayenew & Barbieri 2005)	**15**	System consisting of several aquifers (and aquitards) – gradual infiltration by fissured permeability together with aquifer with porous permeability (Alemayehu et al. 2012)	**15**
		Morphology (elevation, slope gradient, erosion features, etc.)	Steep fault slopes along both sides of the basin generate high runoff, deeply incised gully erosion; reactivation of old landslide bodies	**20**	Rugged relief, with rock outcrops, deeply dissected creeks and erosion channels but also less steep areas with terraced arable land; reactivation of old landslide body	**15**
		Land cover	Deficiency of natural vegetation due to deforestation of slopes – bare soil covers the majority of area	**10**	Intensively cultivated terraced slopes	**0**
External factors	Triggering factors changing over time, acting as a long-term and also as single pulses	**Rainfall**	Bi-modal rainfall pattern (heavy rainfall period from July to August), mean annual precipitation reaches 1,256 mm/year (1990–2013)	**70**	Bi-modal rainfall pattern (heavy rainfall period from July to August), mean annual precipitation reaches 1,748 mm/year (1990–2013)	**75**
		Seismic activity	Tectonic active fault zone near the Ethiopian Rift with relatively frequent earthquakes	**15**	Tectonic active fault zone near the Ethiopian Rift with relatively frequent earthquakes	**25**
		Anthropogenic influence	Densely inhabited area with urban/housing development, changing of natural conditions (morphology and land cover) and water regime; due to town infrastructure, road construction, pipe-lines, quarrying, agricultural activity, deforestation, reforestation etc.	**15**	Agricultural landscape, scattered village development, artificial system of field irrigation	**0**

cause of numerous slope deformations in both areas. The faults of the rift edge can suffer occasional earthquake tremors leading to activation of unstable ground. Finally, human activity has been a specific trigger of landslide activity (especially in the Dessie area) during the last five decades and can also be considered as one of the appreciable external factors.

Table 1 provides a complex overview of the major causes of landslides using a classic assessment approach. The conditions of the studied sites are relatively stable in terms of tectonic structure and geological settings as well as the relatively variable dependence on external influences (e.g. the hydrology regime or morphology and their changes). All of these together form a complete system of interactions of elements/parameters that change over time, and their mutual combination repeatedly creates optimal triggering impulses for geodynamic processes (Figure 1).

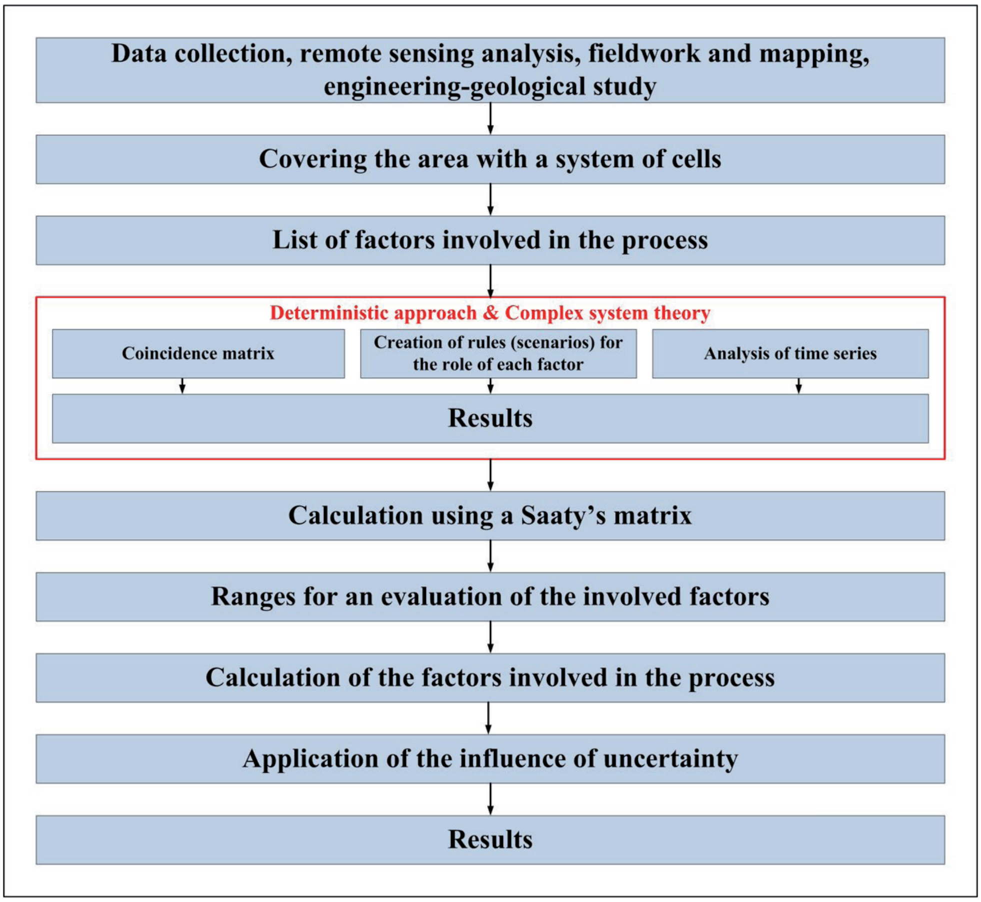

Fig. 2 Flow chart showing the evaluation process.

2. Methods

When performing a multi-criteria evaluation of risks, a method should be used that allows the total value of the risk connected with the landscape and its future exploitation to be evaluated. To be able to calculate such clearly defined risk values for each locality, we proposed a system of finite steps, which enable us to calculate or estimate the crisp risk value for the study sites. In the same time, it has to provide information on the uncertainty or plausibility of this value for future decision making.

It was necessary to create a comprehensive procedure (method) to evaluate a definite size of risk for each site. This procedure should be able to calculate a clear value of risk at the site after certain exactly defined steps and evaluate the plausibility of this value for future decision making. It should be noted that exactly measured real time values or values with the required frequency describing the causative factors are not usually available.

Step 1 – Data collection, remote sensing analysis, fieldwork and mapping, engineering-geological study

The basis for an objective assessment is the maximum amount of relevant data and information. For this purpose the available data and published results of previous studies for each study site were carefully collected. These data provide information especially on the main types of geodynamical processes, geology and geomorphology units. This basis was supplemented with new information derived from digital elevation models (DEMs) and remote sensing data. The slope characteristics were calculated from the available medium resolution SRTM DEM and newly derived high resolution DEMs from ALOS/PRISM image triplets. The SRTM DEM is a homogeneous global DEM with a grid spacing of one arc second corresponding to 30 meters (Farr and Kobrick 2000; Rabus et al. 2003). The ALOS (Advanced Land Observing Satellite) is a Japanese system which was operational between 2006 and 2011 and was primarily dedicated to cartography and disaster monitoring. The triplet consists of three images taken by the PRISM instrument consisting of backward, nadir and forward pointing cameras which enable stereo-processing (Takaku and Tadono 2012). The DEM derivatives such as hillshading and slope inclination allowed us to identify morpho-lineaments which can indicate the tectonic predisposition of landslides. The DEM derivatives also allowed us to carry out a detailed landslide inventory. The concave shape of the head area and the convex shape of the frontal lobe were used for the identification of landslides. We also used typical shades, patterns of open cracks and scarps in the Kompsat-2 image. The very high resolution satellite images acquired by Kompsat-2 were used to obtain information on the land cover of the study sites. The conformity with published inventories (e.g. Ayenew and Barbieri 2005; Fubelli et al. 2008; Suyum 2011; Alemayehu et al. 2012; Abay and Barbieri 2012) was also checked.

During the field investigation the obtained results were validated and new reactivations were identified. The localization of the delimited landslides was compared with the fault zones and lineaments to reveal the possible influence of tectonics on the landslide predisposition. Further possible triggering factors such as precipitation and anthropogenic factors were evaluated. More than 50 years (1962–2013) of rainfall and temperature records measured at the Dessie station and more than 20 years (1993–2013) of rainfall records from the Debre Sina station were provided by the National Meteorology Agency of Ethiopia. These data were used to analyze the distribution of precipitation and temperature variations.

Step 2 – Covering the area with a system of cells

In this case, we covered part of the study area with a regular mesh of cells. This mesh should cover all of the important points, i.e. old landslides, old environmental issues, areas of interest for investors etc.

The study area is a large geographic region, where several sub-areas can be found with very different factors, which have different influences on the stability of the rock massif, i.e.:

– complex geologic conditions,
– different factors caused by human activities.

Due to these facts there is no complex and closed analytic instrument for a precise description of all of the aspects of interest. That is why it was decided to apply a statistical approach with a certain percentage of approximation or an acceptable risk of uncertainty.

The next argument is that the explored processes are non-linear due to the simultaneous engagement of several non-linear influences and their parameters change during time.

For this reason it was decided to use a non-linear approach for describing the process. This approach is based on splitting the large area with different conditions into several smaller sub-areas, where the conditions can be considered to be nearly constant. The criterion for deciding on the suitable size of each sub-area is to reduce the number of different factors in each cell as much as possible; however, the size of these sub-areas should not be too small as it has to reflect the fact that the accuracy of the description cannot be 100% due to the limits given by the available time, costs and technology and, that we are willing to accept a certain risk given by uncertainty.

In practice, the study area is divided by covering it with a rectangular 2D-mesh (or several meshes) with acceptable grid spacing in both perpendicular directions. Then, a coordinate system (X and Y axes) can be assigned to each mesh, which in the next step enables us to create a matrix-like database of cells characterized by their (X,Y)-position in the matrix.

It then becomes possible to use each cell of the matrix to describe the conditions inside each sub-area of an acceptable size, which further enables to use relatively simple descriptive methods.

Step 3 – List of factors involved in the process

In this step, it is necessary to establish a list of all possible factors, which could have any influence on the given process. The inclusion of each factor into the list has to be done independently of its real intensity in any single cell. This means that it should be done from a complex point of view, covering the whole area. These factors have to cover the following scope:

– natural phenomena, such as rainfall, temperature changes, soil susceptibility, evaporation, vegetation cover, degree and velocity of erosion, tidal forces etc.;
– anthropogenic activities, such as cutting of slopes or excavating for roads, deforestation, agricultural activities, civil engineering, pumping of water, exploitation of rivers etc.

In principle, all of the natural factors are of a destructive nature. The human activities are mostly destructive but, under some circumstances, they can also contribute to stability and security.

In our application we assume that a combination of the following factors can characterize a selected locality: hydrology, land cover, anthropogenic activities, vegetation cover, slope characteristics, tectonics, erosion, lithology, engineering-geology, climatic influences and the influence of tidal forces.

Tab. 2 List of considered causative factors.

ID	CRITERION	SUB-CRITERION
1	**Geomorphology**	Slope characteristic (slope inclination, length of slope, slope aspect, morphology affected by old landslides)
		Erosion (sheeting, rilling, gullying, fluvial erosion, undercutting of slopes)
2	**Geology**	Engineering geology (geomechanical properties of rocks and soils, degree of saturation)
		Lithology (thickness, structure, weathering and erosion resistivity)

2	**Geology**	Tectonic (presence of faults and seismicity)
		Hydrogeology (ground water level, aquifer and aquitard)
3	**Soils**	Soils (soil texture, infiltration, soil saturation)
4	**Climatic and astronomic influences**	Climatic influences (cumulative precipitation, extreme precipitation, evaporation and runoff, variation in temperature)
		Tidal effects (solar and lunar tides)
5	**Vegetation cover**	Vegetation cover (vegetation density, vegetation type – grass, shrubs, forest)
6	**Anthropogenic influence, land use**	Anthropogenic influence, with a stabilizing (1) and destabilizing (2) effect (1) drainage, retaining walls, strengthen the surface, reforestation, etc. and 2) induced seismicity, undercut of slopes, changes in the hydrogeological conditions, etc.)

Step 4 – Coincidence matrix and the creation of scenarios for each factor

There are several factors that can have an influence on the geological process. However, these factors do not act on the principle of "each with all of the others, one by one". In other words, the coincidence matrix of these factors is not full because relations between certain factors cannot be equivalent in both directions (Nechyba et al. 2014). For example, rainfall can have an influence on the stability of a slope but it cannot be influenced by stability, etc., therefore the coincidence matrix will not be symmetrical.

Having created a list of possible factors that could have an (even very small) influence on the area, it is helpful to establish a matrix of possible coincidences between these factors. The aim of this step is to exclude relations, which rarely happen in reality. For example, rainfall intensity (factor A) could cause the soil to become slushy (factor B). Thus, we can set up the rule A → B but it does not function in the opposite direction, so it is not necessary to evaluate the relation B → A.

Step 5 – Analysis of time series

Several factors involved in the process can be described by time series. The longer the time series, the more information can be gained from them. However, classic statistical methods cannot reveal certain non-linear information hidden in these time series. Thus, more universal modern methods should be used (Zvelebil et al. 2006).

In the case of the Ethiopian Plateau (two model localities – Dessie and Debre Sina), time series for air temperature and rainfall are available.

Classic methods can also be used to gain as much information as possible from the time series. In this case, the analysis was performed by applying periodograms, correlation, and numerical and graphical methods from the tools of nonlinear science (Zvelebil et al. 2006).

The method based on *periodograms* allows us to calculate statistically important periods in the time series, which are the most significant in the process. This approach can reveal valuable information hidden in the time series. Knowing these periods, we can make conclusions about possible sub-processes, which are incorporated into the total process described by the time series. In principle, decompose the process into certain spectral components characterized by their angle shift φ and amplitude A, using harmonic functions. From these spectral components we create a formula i.e. the sum of a limited amount of harmonic functions with different parameters φ, A, providing us with an analytic instrument, which a) describes the process with a known accuracy (likelihood) and b) can be used for other calculations (forecasting the next development, derivation to know the process velocity etc.).

The method aimed at calculating the *correlation* between two time series makes it possible to obtain information about the grade of dependency between these time series. As an example, the correlation between time series of rainfall and water levels in rivers results in a high correlation coefficient. On the other hand, this method can also be used to reject the idea about a possible dependency between two other sub-processes. Thus, this is an effective instrument for providing an overview of the process as a whole.

For localities where landslides (i.e. unstable rocks) are monitored, the recommended methods for evaluating data are based on the theory of complex systems (Zvelebil et al. 2008) as the interaction and co-operation of two elementary factors can induce dramatically new effects. The unexpected rise of new structures in time-and-space, whose features and relations between them could totally differ from the basic rules, can lead to abrupt qualitative changes in behavior, creation of new features, or possibly even the creation of a new set of different states with unstable and unpredictable development in time and space. The tools for description of such systems can be found in the newest results of basic physical and mathematic research of complex systems. These tools include a phase-portrait in 2D and 3D space, a numeric risk diagnostic based on qualitative differences in time-correlations between residuals in 'near-to-equilibrium' (NTE) and 'far-from-equilibrium' (FFE) time series, recurrence analysis, and power spectra etc.

Step 6 – Calculation using a Saaty's matrix

Having selected the N factors we then create a matrix N × N. The relation "The importance of factor X against factor Y" should be described (by numbers) in each cell of the matrix. Several methods known from economics or statistics can be applied, so we assume the use of a Saaty's matrix (SM) because of its simplicity. The cells of the SM have to be filled in by numbers, which are ratios stating how many times (we assume) factor X is more (or lesser) important than factor Y.

The Saaty's matrix is highly suitable for this purpose. If we begin to fill in the i-th line of the matrix, then there will be a number in the cell with indices [i, j], which states how many times the influence of factor i is higher than the influence of factor j. If the ratio of both influences is 1 : 1, then the value in the cell will be 1. If the importance of the second factor is only 1/3 against the first one, then this ratio can be expressed as 0.33 etc.

Note that on the diagonal there have to be values equal to 1 only because each factor has an importance of 1 compared to itself.

After filling in this matrix, the calculation has to be done for to gain a weight of each factor in comparison to others.

The SM should be defined for various scenarios that describe the possibilities of future development. These scenarios should cover foreseen possible (real) combinations of input conditions, which can occur. In this way, it is possible to be prepared for more hazardous situations in advance. The automatic system for decision support should have access to actual data and after their evaluation it should be able to switch over to another scenario when it finds an extreme change of input conditions (Nechyba et al. 2014). In such a case, the SM has to be re-calibrated (automatically or manually) in order to be in accordance with reality.

As mentioned above, it is important to elaborate scenarios, which count on extreme changes in inputs, i.e. when the stability of the system changes. Let us call them critical scenarios (CS). The CS should cover the entire spectrum of possible hazardous situations, such as heavy rain + soil saturated by water + inconvenient slope + … etc.

Step 7 – Ranges for an evaluation of the involved factors

For the next steps it will be necessary to set up boundaries of possible intensity for each factor.

After setting up the possible minimums and maximums of each factor, the next step should follow. In this step, any possible influence of a factor has to be evaluated from the point of view of what happens, when the intensity of the factor changes. To make this evaluation easier, it is a good idea to split the whole range of the factor into more sub-intervals, which are interesting from certain point of view. In other words, this dividing has to be based on the fact that in most cases different intensities of factors produce different results. For example, a better evaluation of the influence of various air temperatures can be made when the total range of temperatures (i.e. between the maximum and minimum temperatures) has been divided into individual sub-intervals, which cover very low, moderate and very high temperatures. Alternatively, the factor rainfall can be divided into sub-intervals called no rain, low intensity etc. up to heavy rain. Another example could be the factor vegetation cover, which could be divided into sub-intervals of between 0% and 100%.

This dividing has to be performed by giving numeric values of intervals for boundaries of sub-intervals. In the case of the factor temperatures the following set of sub-intervals can be specified:

a) very low temperatures: from -5 °C up to +3 °C,
b) low temperatures: from +3 °C up to +10 °C,
c) moderate temperatures: from +10 °C up to +30 °C,
d) high temperatures: from +30 °C up to +50 °C,
e) very high temperatures: more than +30 °C.

Step 8 – Calculation of the involved factors in the process

In this part of the method we have to set up a value, which can be described by the words how strong is the influence of each factor.

The range of factors that have (or can have) an influence on the process is very wide and their nature can also differ enormously. They mostly cannot be easily evaluated by comparison based on direct (linear) methods. In other words there is no all-explaining rule based on superposition of respective influences of all the factors. In fact, the evaluated factors can be compared only after their values have been transformed into a common comparative basis, which for example could be a scale from 0 to 10 points. Let us call this *evaluation of the value of intensity*.

In our method we used a scale from 0 to 10. The resolution (step) of this scale has to be chosen based on how many values the intensity of the factor can occur. Expressed in mathematical language, we have to map the possible intervals from 0 to 10. The simplest way to do this is by linear interpolation; however, other alternative methods of interpolation (i.e. logarithmic) can be used. The interpolation method should be chosen by experts that understand the problems connected with the occurrence of the factor(s).

Step 9 – Application of the influence of uncertainty

It is also necessary to state that not all of the intensities of the factors have been detected with the same reliability and accuracy. This fact can be expressed by multiplying the value of intensity of the factor by an uncertainty coefficient, which can be set up based on the following example:

1. the intensity of the factor has been determined by direct measurement or laboratory analysis, with high repeatability, also with high plausibility:
   … the uncertainty coefficient can be from 80% to 100%,
2. the intensity of the factor has been gained by interpolation from direct measurements by linear, bi-linear, exponential etc. interpolation:

… the uncertainty coefficient can be from 60% to 80%,
3. the intensity of the factor has been gained by qualified estimation:
… the uncertainty coefficient can be from 30% to 60%,
4. the intensity of the factor has been roughly estimated using comparison based on analogy, experience, qualified estimation etc.:
… the uncertainty coefficient can be from 10% to 30%,

Step 10 – Results

In the end of this step, the total evaluation of risk (TER) connected with the process should be calculated for each cell [i, j] from the numeric values using the above-mentioned procedures, by applying the following formula:

$TER_{i,j} = Sum_k (UC_{k,i,j} \times VFI_{k,i,j})$

where $UC_{k,i,j}$ = uncertainty coefficient of the factor with index *k*, assigned to the cell [*i*, *j*] in the 2D-mesh,
$VFI_{k,i,j}$ = value of intensity of the factor with index *k*, assigned to the cell [*i*, *j*] in the 2D-mesh,
Sum_k = the function summation of all products assigned to the factor with index *k*.

From a mathematical point of view the TER is equal to the scalar product of 2 vectors:
– vector of uncertainty coefficients,
– vector of values of factor intensities.

3. Example

The method described here has been tested on the model localities of the Dessie Graben and Debre Sina landslides. Figs. 3–7 show the examples of the results of each step of the multi-criteria analysis.

4. Discussion

It is necessary to bear in mind that in most cases the risk of landslides or erosion has to be evaluated in sites where there is not enough data available to base the prediction on an evaluation of time series, for example from the area of non-linear dynamics. That is why it is necessary to create and use models, which are able to work out data of a different nature, in different formats, gained by different methods or from different areas. The data can come from actual measurements, from past times, in the form of time series or plain text or even in graphic form, discontinued, from mapping in situ or from remote sensing.

The combined method is based on the principle of a multi-criterion evaluation system, which describes and evaluates the respective criteria from different points of view. For the partial calculation of criteria, it is possible to apply classic statistic methods together with newer methods, such as fuzzy logic, which help to evaluate criteria with limited data sets, described more or less in a qualitative form.

Due to the above-mentioned lack of data there is a question about the plausibility of the results of evaluations made by applying the method we have proposed. In other words, whether realistic results can be gained from the insufficient amount of data or by the simultaneous use of both qualitative and quantitative data. This problem can be solved by introducing the terms certainty and uncertainty. These terms enable us to determine on what level of plausibility the data can be considered in the calculation or on what level of accuracy the calculated result needs to be considered. Instead of one numeric value, this level of accuracy gives us certain fluctuation range, in which the overall result can be found. Together with the knowledge of the possible accuracy gained by this kind of evaluation, we also get a general idea of what data have to be incorporated or improved in terms of accuracy in the future to make the result more precise.

Application of the method requires a multi-disciplinary approach and sufficient knowledge of the issues connected with the area of interest. In addition to knowledge of engineering geology and geomorphology, it is necessary to focus on knowledge from the areas of mathematics, statistics and informatics. Empirical experience should also be applied together with a phenomenological point of view. This means that not only the processes should be described but also the relationships between them.

The combined method enables us to also evaluate natural risks at sites where no evaluation has been performed due to the mentioned lack of data and their different characteristics. By applying this method, a basic overview can be gained in a very short period of time of the actual and future level of risk connected with rockfalls, landslides or erosion in a selected area. Such areas could be in developing countries where the insufficient technical, technological and personal resources prevent continuous and complex monitoring of risk phenomena in order to obtain enough data to analyze and predict possible threats.

The general methodology describes a process, which is suitable also for sites, where there are only limited knowledges about the region and, the high degree of subjectivity must be applied. The methodology had been verified also in other regions, i.e. in a region of North-Western Bohemia, where there are data enough, thus the subjectivity is low and it was possible to calibrate this methodology (Nechyba 2014).

5. Conclusions

The described integrated method is suitable for a basic evaluation of landslide or erosion risks, based on data gained from both historical and actual real-time measurements, from surveying in situ or from remote sensing. These data can be evaluated by classic deterministic methods or by methods from the theory of complex systems.

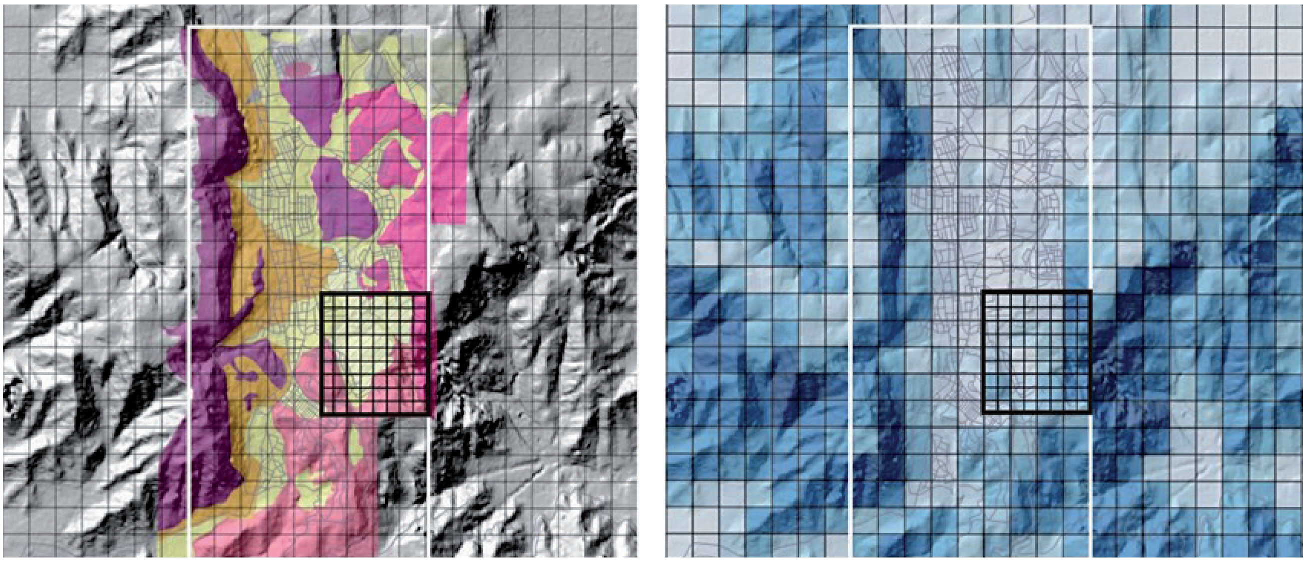

Fig. 3 Example of the "Covering the area with a system of cells" step in two scales (the central and southern parts of Dessie town are marked by a white rectangle represented by single squares of 360 × 360 m, the study area with active landslides is marked by a black rectangle represented by single squares of 180 × 180 m): a) with a geological map, b) with slope inclination in the study nets.

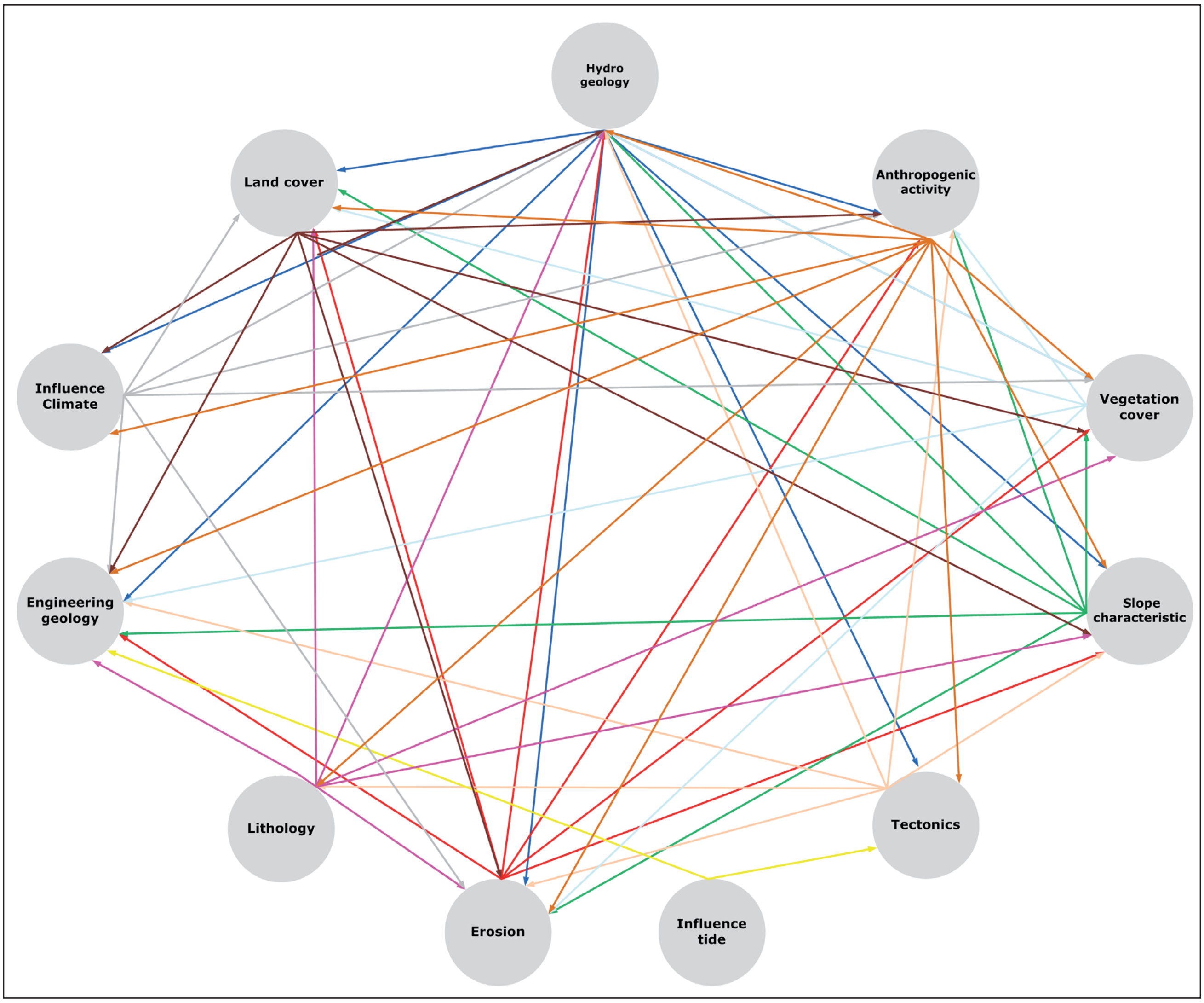

Fig. 4 Example of the "Coincidence matrix" step.

	Crit 1	Crit 2	Crit 3	Crit 4	Crit 5	Crit 6	Crit 7	Crit 8	Crit 9	Crit 10	Crit 11	GA	WEIGHT	
1. Slope characteristic	1	4	1	1	0.6667	0.6667	0.6667	0.6667	0.8	8	0.5	1.088	0.0792	7.92%
2. Erosion	0.25	1	0.25	0.25	0.1667	0.1667	0.1667	0.1667	0.2	2	0.125	0.27202	0.0198	1.98%
3. Engineering geology	1	4	1	1	0.6667	0.6667	0.6667	0.6667	0.8	8	0.5	1.088	0.0792	7.92%
4. Lithology	1	4	1	1	0.6667	0.6667	0.6667	0.6667	0.8	8	0.5	1.088	0.0792	7.92%
5. Tectonic	1.5	6	1.5	1.5	1	1	1	1	1.2005	12.0482	0.7502	1.63267	0.11884	11.88%
6. Hydrogeology	1.5	6	1.5	1.5	1	1	1	1	1.2005	12.0482	0.7502	1.63267	0.11884	11.88%
7. Soils	1.5	6	1.5	1.5	1	1	1	1	1.2005	12.0482	0.7502	1.63267	0.11884	11.88%
8. Climatic influences	1.5	6	1.5	1.5	1	1	1	1	1.2005	12.0482	0.7502	1.63267	0.11884	11.88%
9. Tidal effects	1.25	5	1.25	1.25	0.833	0.833	0.833	0.833	1	10	0.625	1.35978	0.09898	9.9%
10. Vegetation cover	0.125	0.5	0.125	0.125	0.083	0.083	0.083	0.083	0.1	1	0.0625	0.1358	0.00988	0.99%
11. Anthropogenic influence	2	8	2	2	1.333	1.333	1.333	1.333	1.6	16	1	2.17577	0.15838	15.84%

Fig. 5 Example of the "Saaty's Matrix" step.

SUB-CRITERION	WEIGHT	EVALUATION	RISK
1. Slope characteristic	0.0792	6,1	0.48312
2. Erosion	0.0198	4,8	0.09504
3. Engineering geology	0.0792	5,5	0.4356
4. Lithology	0.0792	5,3	0.41976
5. Tectonic	0.11884	2	0.23768
6. Hydrogeology	0.11884	1,8	0.213912
7. Soils	0.11884	6,2	0.736808
8. Climatic influences	0.11884	2,4	0.285216
9. Tidal effects	0.09898	1,1	0.108878
10. Vegetation cover	0.00988	6,8	0.067184
11. Anthropogenic influence	0.15838	7,2	1.140336
SUM	1	49.2	4.223534

Fig. 6 Example of the "Calculation of the involved factors in the process" step.

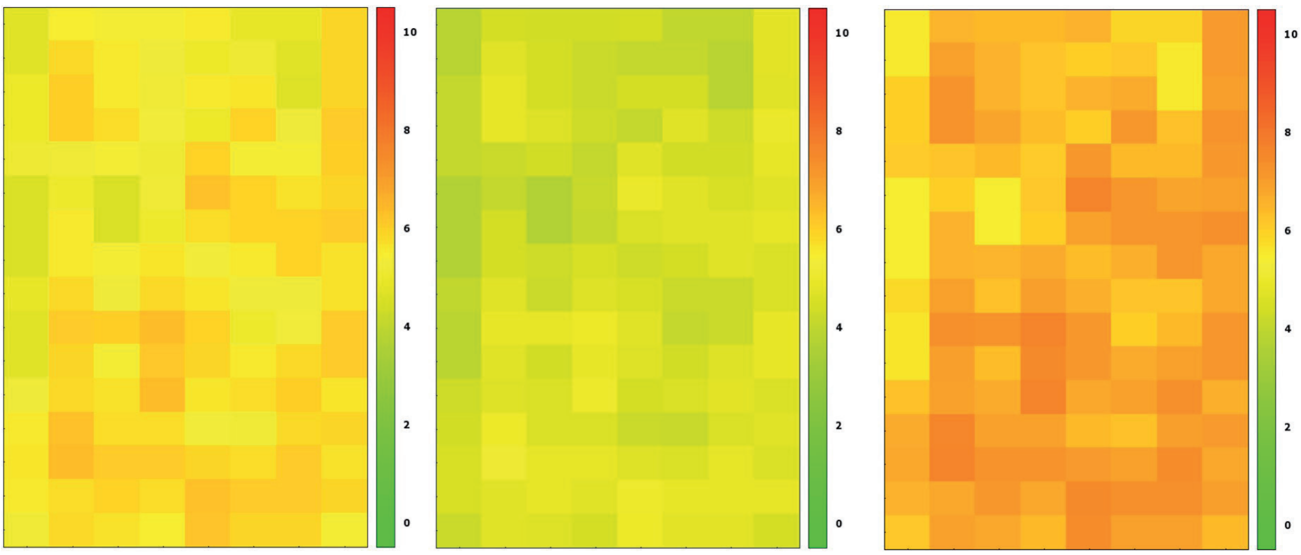

Fig. 7 Example of the "Results" step (risk assessment in Dessie graben): a) general result b) minimal risk c) maximal risk.

The combined integrated method has been tested on two selected localities with landslide hazards on the border of the Ethiopian Highlands and the Main Ethiopian Rift. The result gives a basic overview of the susceptibility to risks for the utilization of the study area. At the same time, it presents a level of data relevancy, which can influence possible uncertainty during risk evaluation and forecasting. The method is suitable for a prompt risk evaluation and swift decision making. The method represents an effective tool in the case of incomplete geological and geomorphological data.

A combined method, exploiting the advantages both of the deterministic approach and an approach from the theory of complex systems, brings significant added value for risk evaluation of certain types of sites.

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RESUMÉ

Kombinovaná metoda pro hodnocení rizik svahových pohybů a náchylnosti k erozi na území Etiopské vysočiny

Řešitelský tým česko-německého výzkumného projektu se zaměřil na vytvoření nové kombinované metody, která by byla schopna ohodnotit rizika související se svahovými pohyby a erozí v oblasti Etiopské vysočiny. Realizace hodnocení dat a rozhodování z pohledu rizik se dnes uplatňuje ve stále složitějších podmínkách. Přírodní rizika tvoří velmi komplexní, dynamický systém, který není vždy stabilní z pohledu chování a jeho popis může být složitý a ne vždy spolehlivý. Je třeba si uvědomit, že problematika hodnocení nespočívá pouze v samotných metodách hodnocení, ale obecně i v dostupnosti dat, jejich kvalitě a relevantnosti. Procesy hodnocení a rozhodování tak vyžadují nové kombinované přístupy, založené na exaktních metodách, s využitím kvalitativních i kvantitativních informací, a se zkoumáním přirozených nejistot a neurčitostí.

Nová kombinovaná metoda vychází z klasického deterministického přístupu a z teorie komplexních systémů. Pro vlastní hodnocení využívá data z dálkového průzkumu země, vlastního terénního průzkumu a dostupných časových řad sledovaných parametrů. Metoda využívá z části kvalitativního hodnocení, kdy pro tyto účely je možné aplikovat principy umělé inteligence. Metoda vycházela z poznatků většího počtu lokalit, ověřena byla na dvou lokalitách nacházejících se v Etiopské vysočině (Dessie, Debre Sina).

Nová metoda přináší nástroj, pomocí něhož je v relativně krátké době možné provést základní ohodnocení rizik sesuvů a eroze, a to i na lokalitě, kde doposud neexistují relevantní data k jejímu stavu. Prezentovaný výsledek do určité míry obsahuje neurčitost a nejistotu, které jsou ovšem zcela jasně definovány. Metoda tak připouští využití i subjektivně hodnocených či zabarvených informací, a tyto informace dokáže formulovat a efektivně využívat.

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