ANALYSIS OF SIGNIFICANCE OF ENVIRONMENTAL FACTORS IN LANDSLIDE SUSCEPTIBILITY MODELING: CASE STUDY JEMMA DRAINAGE NETWORK, ETHIOPIA

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ABSTRACT

Aim of the paper is to describe methodology for calculating significance of environmental factors in landslide susceptibility modeling and present result of selected one. As a study area part of a Jemma basin in Ethiopian Highland is used. This locality is highly affected by mass movement processes. In the first part all major factors and their influence are described briefly. Majority of the work focuses on research of other methodologies used in susceptibility models and design of own methodology. This method is unlike most of the methods used completely objective, therefore it is not possible to intervene in the results. In article all inputs and outputs of the method are described as well as all stages of calculations. Results are illustrated on specific examples. In study area most important factor for landslide susceptibility is slope, on the other hand least important is land cover. At the end of article landslide susceptibility map is created. Part of the article is discussion of results and possible improvements of the methodology.

Keywords: slope movements, natural hazards, susceptibility analysis, Ethiopian Highland

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1. Introduction

Ethiopia like other developing countries depends on domestic agricultural production, struggling with infrastructure and healthcare is also at a low level. Among these factors there is also added impact of catastrophic natural processes. Landslides in this area have caused enormous material damage and also human deaths. Effects of those losses are huge and locals are dealing with them difficulty. Therefore, prevention should be a priority concern.

This paper focuses on analysis of significance of environmental factors in landslide susceptibility modeling. Aim of the paper is to describe methodology for calculating significance of environmental factors in landslide susceptibility modeling and present result of selected one. The main environmental factors in this area are: slope, altitude, lithology, land cover, distance from geological boundary and distance to river. The methodology for landslide susceptibility modelling that was used is also described. Based on this methodology results, the importance of the factors is concluded. Main idea is comparison of the real distribution of slope movements against the expected occurrence across the classes of input layers. Used methodology is universally applicable and the results it generates match reality well. Map of landslides susceptibility based on used methodology is presented.

The knowledge of the landslides spatial distribution and significance of their environmental factors can be a key driver in landslide protection which is the reason for creating susceptibility models. Models are created with aim to identify the places where these phenomena occur most frequently and where the probability of occurrence of this phenomenon is the highest. These models are often created as a result of intersection of environmental factors and triggering factors. These factors have been described in the previous chapter. The process and inputs of these models are divided into several groups. Their results are however always maps of susceptibility. Susceptibility and vulnerability maps usually divide study area into several zones according to the probability of occurrence of the phenomenon.

Soeters, van Westen 1996, van Westen et al. 1997a, van Westen et al. 1997b developed a classification model for evaluating the landslide hazard. Divides them into: inventory, heuristic, statistical and deterministic. Overview of these methods was also done by J. Klimeš (Klimeš 2003; Klimeš 2007).

Beside quantitative methods most dominant are subjective approaches or semi-subjective approaches, where authors set importance of input parameters. Regarding the works in Ethiopian highlands area various approaches and methods were used. At semi-subjective study from Dejen-Gohatsion location performed by Ayele et al. 2014 Weighted Linear Combination (WLC) method were applied. This statistical approach takes reclassified raster (0–255) layers for each parameter and then combine them together to get landslide susceptibility map. They consider seven influencing factors: Groundwater, Geology, Slope, Aspect, Structure, Land Use/Land Cover and Drainage conditions. Weakness of this study is in reclassification step where Ayele is working with assumptions about landslide occurrence, such as: with increasing

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Tab. 1 Pair wise comparison matrix.

Parameters	Geology	Groundwater	Drainage	Slope	Structure	LULC	Aspect
Geology	1						
Groundwater	1	1					
Drainage	5/7	5/7	1				
Slope	5/7	5/7	1	1			
Structure	3/7	3/7	3/5	3/5	1		
LULC	1/7	1/7	1/5	1/3	1/3	1	
Aspect	1/7	1/7	1/5	1/3	1/3	1	1

Source: Ayele et al. 2014, p. 26.

slope number of landslides is increasing, or with increasing distance from river channel number of landslides is decreasing. These assumptions he then apply as reclassification rule. As results they got seven raster layers on scale 0–255, the higher the number the higher the landslide occurrence and vice versa. After the standardization to common scale of each controlling factor, weight is given for each layer based on pair-wise comparison of two data layers at the same time, using pair-wise comparison.

Another weakness is that ratings assigned during the pair-wise comparison are subjective based on the knowledge from the fieldwork. These pairwise comparisons are then analyzed (analytical hierarchy process) to produce a set of weights that sum to one. The larger the weight means the more influencing is the factor. Highest importance was setted to geology and groundwater conditions (both 24%), then slope and drainage (17%). Aspect and Land cover have lowest importance on landslide occurrence (3%). Pair wise analysis for landslide assessment was also performed by Nechyba et al. 2016. In this work, there go beyond standard building of factors matrix (11 input layers) and they add uncertainty parameter.

Dejen-Gohatsion location was also study area in Asfaw (2010). Author is comparing two different approaches to landslide susceptibility. One is van Westen et al. (1997b) methodology, which is described later in results chapter. Briefly it compares expected occurrence of landslide with real occurrence. The higher is the ratio of real to expected occurrence the more favorable conditions for landslide occurrence. Second is pair pair-wise analysis in combination with certainty factor.

Asfaw also pointed out that landslide impact on other factors is often forgotten. For example large landslide significantly changes land cover of the area or hill slope is lowered by landslides. For this reason he didn't use standard layers, but reconstructed layers. In total he used seven input layers for his model, including: altitude, slope, aspect, lithology, landcover, proximity to drainage lines and proximity to road.

The factor proximity to drainage lines shows little impact on landsliding just like in first method. On the other hand proximity to road factor shows a clear indication of the influence of the road in landslide occurrence. Regarding slope class 15°–30° has a CF value of 0.42 (on scale −1;1) whereas slope class 30°–45° has a CF value of 0.78. The higher the value, the more favorable for landsliding. The correlation coefficient between those two methods shows a strong correlation (0.89).

Completely other approaches were used by Maerker et al. 2016 to predict the potential spatial distribution of landslides they used two methods: classification regression tree approach and mechanical statistics method. The first method is based on stochastic gradient boosting (so called boosted regression trees). This method constructs additive regression model which is optimized by least square method in each iteration. The second Maximum Entropy Method (MEM) is based on estimating of distribution function where entropy is maximized. Both methods are fully processed automatically. Model performance parameters show better results for BRT, that outperforms MEM. However MEM still shows good results. Regarding the results both models calculate slope as a most important variable with contribution around 30%.

2. Study area

The study area is located in the central Ethiopian highlands, about 200 kilometers north of the Addis Ababa,

Fig. 1 Location map of the study area.

east of Fiche village (9°43´N 38°54´E). The area is artificially created around the watercourse, left tributary of the Jemma river. It starts at the east where the channel is deeply incised into the valley, the west boundary is a flat area before river confluence with the River Jemma. South border of the area is determined by the watercourse itself. North boundary is defined by highest degree of the structural terrace (slightly extended).

This area has a uniform morphology, which changes beyond borders significantly. Whole area has an elongated shape with an area of about 50 km^2.

Maximum altitude is 2676 m a.s.l., and lowest 1381 m a.s.l. Main soil types in the region are leptosols and vertisols. Vertisols are heavy soils characterized by high content of clay with typical vertisol effect, ability to absorb very high amount of water, but when the soil cracks. As a result of that big cracks and fissures appear where soil erosion fasten up. Leptosols are shallow young soils on solid rocks with high stoniness. In this region mainly litosols can be observed.

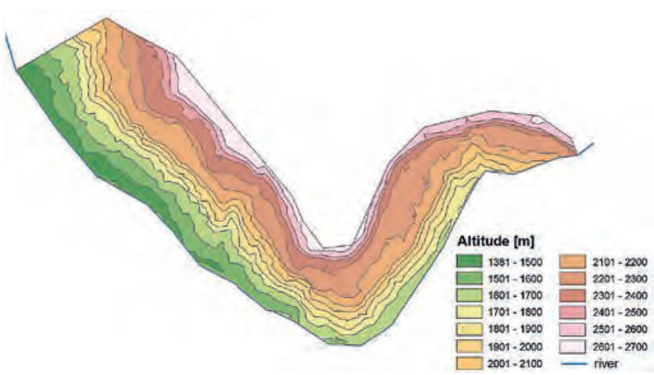
Regarding the weather conditions, major influence has altitude (beside geographical location). Temperatures are quite steady during the year without fluctuations. Average temperature is about 20 °C. During winter months northeast wind brings dry continental air, during summer months there flows humid south monsoon. Topography has major influence on precipitation distribution in the region. Lowest precipitations are in the northern part (500–1000 mm/year) and are increasing to the southwest (1800 mm/year). Also distribution over the year is highly irregular, over 80% of the year precipitation amount is concentrated between July and October. Common landcover is low vegetation, grasses, shrubbery in combination with fertile ground. This distribution of landcover is a result of strongly seasonal precipitation and intensive soil erosion.

In study area six geological units can be identified. They are arranged in strips parallel with river at the bottom of the valley. Those strips also match with topography along the region. With increasing distance from the river the altitude is rising. The river bed is composed of alluvial sediments, mesozoic claystone, siltstone and sandstone. With the further away from the river there are layers of sandstone, which at the level of structural terrace ends and merges into belt of lower tertiary basalts. This very narrow strip is covered with tuf sediments intermixed with basalts. This unit occupies a dominant part of the territory. Further from the river higher tertiary basalts cover this unit. This layer forms the edge of another structural terraces.

3. Environmental factors influence for landslide occurrence

For landslide susceptibility studies, the knowledge of environmental factors in study area is crucial. Environmental factors are mostly described as set of selected physiogeographical characteristics of the area. Combination of those factors can cause slope movement even without any additional trigger (rain, earthquake …). Commonly those are the main environmental factors causing slope movements: slope, altitude, lithology, land cover, soil characteristics, vegetation coverage and others. Also people play important role because his acting changes natural characteristics (deforestation, channel changes, terraces building). To evaluate these, remote sensing techniques can be really helpful. But even so, these methods were not widely used in slope movement researches until end of 90s (Mantovani et al. 1996).

Altitude is one of the factors affecting slope stability. Main assumption is that intensity of exogenous processes increases with rising altitude. Exogenous processes disrupt the slope surface which leads to lower stability. As mass movement processes are defined as movement of the material down the slope by gravity (Summerfield 1991, p. 167) then with an increase in the slope the gravitational force acting on the slope material will increase as well as the possibility of slope movement. Clerici et al. (2002) says that slope is commonly regarded as the most important factor in slope stability, this is supported by researches of Woldearegay (2013) or Broothaerts et al. (2012). Land cover is another factor affecting slope stability. In general vegetation coverage via root system



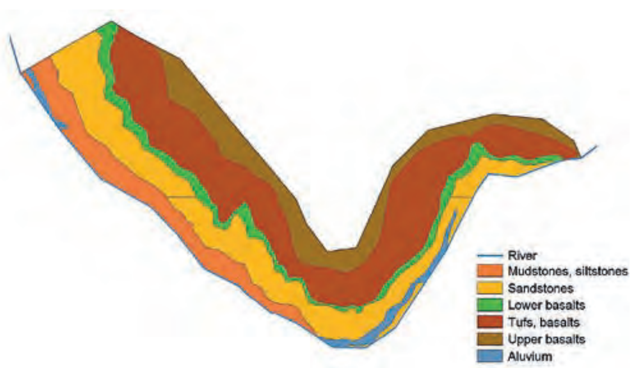


Fig. 2 Geological and topographical map of study area.

has significant stabilization effect on surface. The deeper the root system is the more stable the surface is. Root systems can protect slope from shallow landslides but can not protect from deeply based landslides (Woldearegay 2013). Lithology in meaning of description of the geological substrate plays an important role in slope stability. Rocks differ in properties like hardness, jointing, color,.. Those properties are quantified and called geomorphological resistance. Beside that geology substrate other geology related factors like layers sequence, cracks and faults occurrence or deposition of layers can affect landslide susceptibility. Geological boundary is commonly perceived as zone with lower resistance to exogenous processes, often with occurrence of joints or fractures. Also slope aspect can be considered in some areas. Beside those predisposition factors also triggering factors like precipitation or seismicity are very important for landslide predictability.

4. Data and methods

Input data can be divided into two parts: remote sensing data (DTM) and field research data (landslide layer). Mapping of the landslides was done via Google Earth (ASTER) and supported by fieldwork verification. Main source of the remote sensing data were prepared in Water resource management and environmental protection studies of the Jemma basin for improved food security project (Šíma et al. 2009). Totally was mapped over 200 landslides that were used for setting factors significance. Those landslides are divided into three categories: landslides, topplings and falls and flow movements.

Tab. 2 Class and landslide representation and calculated importance of slope parameter.

Class	Relative class representation	Relative landslide representation	Importance V_{CP}	Rank (Descending)
1	10.27%	0.41%	0.04	3
2	13.53%	0.41%	0.03	2
3	15.49%	1.65%	0.11	4
4	13.10%	6.61%	0.50	5
5	11.54%	9.92%	0.86	6
6	10.79%	13.64%	1.26	7
7	9.15%	16.12%	1.76	8
8	6.75%	17.36%	2.57	9
9	4.01%	12.40%	3.09	10
10	2.60%	8.68%	3.33	11
11	1.63%	6.20%	3.79	12
12	0.73%	3.31%	4.53	13
13	0.27%	2.07%	7.72	14
14	0.13%	1.24%	9.73	14
15	0.02%	0.00%	0.00	1

For getting results from collected data own methodology had to be used. It's not completely new approach, it's based on van Westen's statistical index method (van Westen et al. 1997b). Instead of using polygon data and pixel information, it's transformed to point data layer. Basically main idea is evaluating of significance as ratio of density of slope deformations in the parameter class and density of slope deformations within entire area. If there are more landslides in the parameter class than the class represents within entire area, then this parameter class is favorable for landslide occurrence. For example if there are 50% of the deformations in a class which represents only 30% of the area then it's favorable, if there are 50% of the deformations in a class which represents 70% of the area then it's infavorable.

Using of natural logarithm is optional and causes stretching of the values. With logarithm, results scale is $(-\infty;+\infty)$ with threshold value of 0. Without logarithm it's $<0;+\infty)$ with threshold value of 1.

Formula for class importance, van Westen et al. 1997b:

$$\ln \mathrm{W_i} = \ln\left(\frac{\mathrm{Densclas}}{\mathrm{Densmap}}\right) = \ln\left(\frac{\frac{\mathrm{Npix(Si)}}{\mathrm{Npix(Ni)}}}{\frac{\sum \mathrm{Npix(Si)}}{\sum \mathrm{Npix(Ni)}}}\right)$$

Wi is the weight given to a certain parameter class (e.g. a rock type, or a slope class).

Densclass is the landslide density within the parameter class.

Densmap is the landslide density within entire map.

Npix(Si) is number of pixels, which contain landslides, in a certain parameter class.

Npix(Ni) is total number of pixels in a certain parameter class.

Based on the other landslide susceptibility works from Ethiopian highlands (Ayele et al. 2014; Asfaw 2010; Ayalew, Yamagishi 2004; Ayenew, Bariberi 2005; Zvelebil et al. 2010) main environmental influencing factors were identified: slope, altitude, lithology, land cover, distance from geological boundary and distance to river.

At the beginning all mapped landslides were transformed into point layers and spatial information from underlying datasets were extracted and assigned to them. As a result we had a landslide layer with geology, slope, altitude etc. for each landslide. After this preparation importance of each layer class could be calculated. For determining classes importance was used own method based on Van Westen et al. (1997b) approach.

$$V_{CP} = \left(\frac{R_{CP}}{RA_{CP}}\right)$$

V_{CP} is importance of class C of the parameter P.

R_{CP} is relative distribution of landslides in class C of the parameter P.

RA_{CP} is relative are of the class C of the parameter.

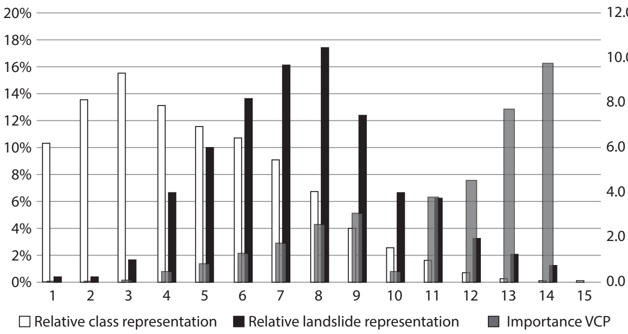


Fig. 3 Class and landslide representation and calculated importance of slope parameter (secondary axis).

Tab. 3 Environmental factors significance.

Parameter	Average importance	Parameters order	Relative factor significance V_{RP}
Lithology	1.04	4	14%
Altitude	1.23	5	16%
Slope	2.81	6	38%
Distance to water course	0.92	3	12%
Land Cover	0.67	1	9%
Distance to geological border	0.79	2	11%

Final class importance is in <0;∞) interval. The lower the values the lower impotance of the class. The higher the values, the higher is the class importance. This formula represents rate of expected occurence of landslides in each class of certain parameter. If the relative occurence of the landslides in a class is higher than relative area of this class (values higher than 1), then this class is favorable for landslide occurence and vice versa. Main advantage of this method is its universality, it can be used in any location with various input data. It's also using an objective approach to evaluate the gathered data without human factor that can affect results accurancy. Also this approach can be completely automatized by writing short script or model that just need landslides dataset and various physiogeographical input data and it will do all the calculations by itself and present the results at the end. Described methodology has some applicable limits, those are described in discussion part.

All those results were unified to a same range of values: 0–255 (using reclassify tool in ArcGis). Importance of each environmental factor was calculated as arithmetic average of all class' significances.

$$V_P = \frac{1}{n}\sum_{P=1}^{n} V_{CP}$$

The predominant influence for landslide occurrence has a slope followed by the altitude and lithology, the smallest is landcover.

5. Results

Main impact on landslide occurrence has a slope. This might be caused by terrain setting in the study area. Area consists of three level of terraces which are separated by terraces levels with very steep slopes (Figure 2). Those parts of the area have highest representation of landslides. Maerker et al. (2016) conducted similar study where same input data were used. In their study two different methods for predicting the potential spatial distribution of landslides were used: classification regression tree approach and mechanical statistics method. Both methods resulted in same results as our study, proposing slope as a major factor for landslide susceptibility.

From calculated results above it's easy to create susceptibility map of landslides for study area. For example LSI – Landslide Susceptibility Index methodology can be used. This approach main idea is to calculate susceptibility for each pixel in the area, to do so we used Weighted Overlay tool. As input significance of parameters (weight) and reclassified data layers based on importance of each class were used. Generated raster had to be reclassified again, so we get map with susceptibility classes. There are many methods for dividing raster into classes, such as the equal interval method, the natural break method etc. In this study, the manual classification method by Galang (2004) was used. This method is based on the assumption that the expected number of landslides in the higher landslide susceptibility class equals two times of the expected number in the next lower susceptibility class. Based on this rule, the raster was reclassified

Tab. 4 Landslide distribution in reclassified susceptibility raster.

Susceptibility class	Area representation	Landslide distribution
1 – Low	40%	6.6%
2 – Middle	27%	13.6%
3 – High	16%	27.3%
4 – Very high	17%	52.5%

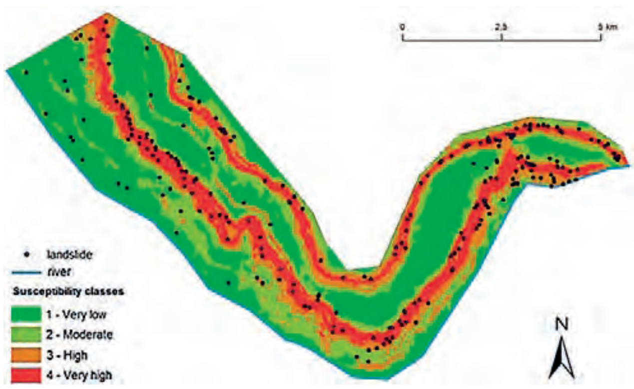


Fig. 4 Landslide susceptibility map with mapped landslides.

to the four classes. As you can see in the map lowest susceptibility class represent almost half of the study area and less than 7% of the landslides are distributed in this class. On the other hand Very high susceptibility class represent only 17% of the area with more than 50% of the landslides are in this class.

6. Discussion

Results of the methodology can be compared to other work from this region (Aeyele et al. 2014). The influence of the distance to the river corresponds with his results. Also results of influence of distance to geological boundary are almost identical 10.3% vs. 11%. Distance to the river has effect of 17%, in my then 12%. This difference can be caused by linear character of input layer. Lineary mapped river represents the streamline and not channel itself which is much wider (sometimes up to 400 m). Regarding differences in other parameters significance, Ayele et al. (2014) calculated considerably lower influence of slope (17%) and higher impact of lithology (24%). Differences can be caused by human factor which is involved in Ayele's methodology where he calculated influences of the classes of each parameter based on his presumptions. For example "with increasing distance from river the number of landslides will decrease". Used methodology is purely statistical, so it avoids these presumptions, which do not have to be true. In case of mentioned distance to river channel Ayele doesn't operate with liner layer problem described above.

Weakspot of used methodology is that landslides were mapped as points which were placed on separation edge. Here we worked with presumption, that most landslides are triggered in upper part. We are aware that this doesn't have to be true, but results characterize distribution well. This has to be considered especially when work is focused in other regions with different physiogeographical characteristics.

As already mentioned, the created model represents the distribution of slope movements well. Since the generated methodology is universal and all calculations are determined by uniform mathematical steps, this methodology is applicable in other areas of the world. As it is a simplification of reality, it is necessary to access the results in such a way. Furthermore, we want to highlight other facts concerning the data that was reflected in my results.

Input data we worked with have different resolution and accuracy, which significantly affects the results accuracy. For example, used digital elevation model with a resolution of 30 meters, from which altitude layer was created, generates the highest slope of 75°. During fieldwork were clearly found places with higher inclinations. This can be due to the method of calculation of slope and the resolution of the incoming digital model which leads to smoothing extreme values.

You can not use data layers with significantly smaller scale than the scale of mapping work. This is case of land cover layer, which has bad resolution. With the low variability of land cover and the similarity of classes it was possible to use this map even with lower resolution. Layers with lower scale would be useless because they do not provide sufficiently accurate information about the distribution.

Probably the most important part was mapping work, during which the landslides were localized. To ensure the quality of this input several times cuts that Google Earth offers has been used. Ability to compare multiple time slices in one view appears to be an advantage, but on the other hand, it is also a disadvantage. Mapping should always be done in the latest data and use the older images as a helper. If it was mapped in older images, the verification of older deformations in the field would be very difficult. Identification of slope movements from satellite images is of course possible and is lately widely used, but the uncertainty is rising if image quality is low. Therefore, this methodology is generally recommended for smaller areas with good image quality. Mapping from satellite images is time consuming and the larger the area and the number of deformations, the more demanding is field verification.

Created methodology is applicable to point marks, but also to the areal elements, where instead of the number of occurrences the relative area will enter into the model. This is one of the possible improvements of this model if they are available background layers in the adequate resolution. Another option for improvement is to run the model on different data sets of landslides (separately for landslides, rock falls and topplings and flow movements). For such extensions greater quantity of the mapped elements would be necessary. For general information, which areas are unsafe for residents, it is sufficient to use a common data file.

The strength of this methodology is the possibility of its complete automation (beside the mapping part). All subsequent procedures can be automated, for example by creating a model in the Model Builder in ArcGIS.

7. Conclusion

The area of this work is located in one of the world's poorest countries, Ethiopia. Residents of Ethiopia are dependent on their own agricultural activities, infrastructure is not developed enough which result is that the trade takes place more on a local scale. To these factors and added impact of catastrophic natural processes are residents exposed on daily basis. One of them are landslides, which in this area have resulted in enormous material damage, but also human death. Impacts of these losses for locals are huge and sometimes even existential. Without knowledge of the susceptibility to these movements, it is impossible to prevent them effectively.

In this study we conducted a statistical analysis using van Westen modified approach to analyse the main driving factors to assess landslides in the Jemma basin in Central Ethiopia. Therefore, we mapped the landslides in a small tributary of the Jemma catchment showing typical characteristics of the entire basin. The mapping of forms and features was performed using GE high resolution images followed by terrain work.

Results in general well corresponds with other works within the region. Totally six input factors were analyzed: altitude, slope, lithology, land cover, distance to river and distance to geological boundary. As parameter with highest influence on landslide occurrence was calculated slope with 38% share followed by altitude and lithology (around 15%). On the other hand land cover had lowest impact (9%). Applied methodology is universal and can be used at other locations across the world. Strengths and weaknesses of the methodology, including the possibility of further improvement are discussed in detail in the discussion.

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RESUMÉ

Analýza významnosti předběžných faktorů v modelování náchylnosti ke svahovým pohybům: Případová studie povodí Jemmy, Etiopie

Článek podrobně popisuje metodiku stanovení významnosti jednotlivých předběžných faktorů v modelování náchylnosti ke svahovým pohybům. Jako zkoumaná oblast byla vybrána lokalita Portugalský most, která je svahovými pohyby významně postižena. V první části jsou v krátkosti popsány jednotlivé vstupní vrstvy a jejich vliv na stabilitu svahu. Většina práce se věnuje rešerši dalších metodik používaných k těmto modelům a návrhu vlastní metodiky. Tato metodika je na rozdíl od většiny používaných metodik čistě objektivní, tedy není do výsledků nijak možno zasahovat. V článku jsou dále popsány všechny vstupy a výstupy metodiky, je představen popis jednotlivých fází výpočtu. Výsledky jsou ilustrovány na konkrétních příkladech. Ve zkoumané oblasti je nejvýznamnějším faktorem sklonitost naopak nejméně významný je vliv land coveru. V samotném závěru jsou tyto výsledky použity pro vytvoření samotné mapy náchylnosti ke svahovým pohybům. Součástí článku je též diskuse dosažených výsledků včetně možných vylepšení.

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