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Landslide susceptibility modeling with generalized additive models – facing the heterogeneity of large regions

H. Petschko, R. Bell & T. Glade
Department of Geography and Regional Research, University of Vienna, Austria

A. Brenning
Department of Geography and Environmental Management, University of Waterloo, Ontario, Canada

ABSTRACT: Landslide susceptibility maps are prepared worldwide on local, regional or national scale to identify regions or hillslopes that might be prone to landslides in future. Furthermore, with increasing frequency provincial governments and other stakeholders demand for susceptibility maps on the scale of a province or a state aiming at hazard mitigation.
Especially on regional to national scale special adjustments have to be applied to statistical modeling methods to achieve a good characterization of the study area and to derive reliable susceptibility maps. In the analysis of large study areas new challenges arise regarding data availability and the proper consideration of its lithologic and/or morphologic heterogeneity. The main objective of this study is to model landslide susceptibility for shallow landslides for the province Lower Austria (15,850km²). In our study design we propose to fit and validate a generalized additive model (GAM) for regions that have unique morphological characteristics, which facilitates the identification of respective predisposing factors for landslides that might vary among the morphological units.

1 INTRODUCTION

Landslides cause enormous economic losses as well as fatalities worldwide. To prevent from future damage landslide susceptibility maps have been identified as a powerful tool. These maps can be implemented in spatial planning strategies, which is an important step to avoid future economic losses and fatalities. Numerous publications show that landslide susceptibility maps have been derived on different scales ranging from local site scale to continental scale (Günther et al. 2011; Dikau & Glade 2003; Bobrowsky & Domínguez-Cuesta 2011; Malet et al. 2011; Ferentinou et al. 2011; Trigila et al. 2011).

The main objective of our ongoing project is to derive consistent landslide susceptibility maps for shallow landslides in the province of Lower Austria. These maps should be ready to use by municipal authorities on a scale of 1:25,000. However, in this study we focus on one aspect of the project, which addresses the high heterogeneity of Lower Austria regarding the morphology and the challenges that arise with that.

Our hypothesis is that this heterogeneity is mainly associated with changes in lithology that brings along spatially variable characteristics of slope stability and predisposing factors of landslides. To meet these challenges a study design has to be set up to facilitate the best characterization of the study area. The analysis of this hypothesis and the study design are presented in detail in this contribution.

We use the statistical method of generalized additive models (GAM) for modeling. The application of GAMs for landslide susceptibility modeling is relatively new (Brenning 2008, Jia et al. 2008; Park & Chi 2008, Goetz et al. 2011) whereas generalized linear models (linear or logistic regression) have widely been facilitated to landslide susceptibility modeling (e.g., in Atkinson & Massari 1998, 2011, Bell 2007, Brenning 2005, Van Den Eeckhaut et al. 2006). The main difference between these approaches is the possibility to model nonlinear relationships between dependent (location of landslide points) and explanatory variables (i.e. slope angle, profile and planar curvature) with a GAM (Hastie & Tibshirani 1990, Brenning 2008).

2 DATA

The data available comprehensively for the entire study area contain information on the location of landslides and on the topography, land cover and lithology. The landslide inventory mapping performed to identify the location of former landslides is described in section 4.1. The most important data set for derivation of topographic parameters is a DTM with a resolution of 1m x 1m that was accomplished by airborne laserscanning (ALS) data. Additionally, an orthophoto from the year 2007 was available. Both, the DTM and the orthophoto are by courtesy of the Provincial Government of Lower Austria. Furthermore, land cover data derived from satellite imagery by our project partners from “Joanneum Research” (Graz) with a resolution of 10m x 10m and a lithological map with a scale of 1:200,000 (Source: Geological Survey of Austria, enhanced by Austrian Institute of Technology-AIT) are available. More details on the data preparation and usage in the analysis are given in section 4.1.

3 STUDY AREA

Lower Austria is the North-Eastern province of Austria (Fig. 1a). The entire province has a size of about 19,000km². Landslide susceptibility maps have to be modeled in particular for a region mainly south of the Danube with an area of about 15,850km².

However, to develop the study design three districts of Lower Austria, namely Amstetten, Baden and Waidhofen/Ybbs, were chosen as test study area in this study. These represent the main geological units of Lower Austria but cover a smaller area of 2072 km² which is of advantage regarding shorter data preparation and computation times. Furthermore these districts show differences in the landslide density in the inventory data, which was of importance to test the performance of the model.

The main geological units in Lower Austria are the Bohemian Masif with granites and gneiss, the Molasse Zone with clastic sediments, the Flysch Zone with sandstone and marls, the Klippen Zone with clays and marls, the Northern Calcareous Alps (N.Calc. Alps) with dolomites and limestone (with marls) and in the south the Eastalpine Zone of Paragneiss, Schists and Phyllites.

Figure 1 shows the lithological units and respective bedrock materials in the test study area. In Table 1 their relative area, landslide density and mean arithmetic slope angle is presented. According to the bedrock material the lithological units show very different geotechnical characteristics which have an influence on the general slope stability. The Flysch Zone, for example, contains sandstones and marls which are known for being more prone to landslides in Lower Austria compared to lithological units containing dolomites, limestones or granites.

4 METHODS

4.1 *Data preparation*

The data on DTM, land cover and lithology, which comprises the data basis for the sampling of the explanatory variables, was set to the same spatial extent and resampled to a raster with 10m x 10m

Figure 1. a)Location of Lower Austria and the capitals of the districts Amstetten, Baden and Waidhofen/Ybbs. The grey colour shows a hillshade map of the study area. b) Lithological map of the test districts. N.Calc.Alps = Northern Calcareous Alps. Data source: Geological Survey of Austria and AIT.

Table 1: Comparison of the lithological units in the test districts: (a) Proportion of sampled points in the unit to sampled points in the test study area (2% of all grid cells), (b) Landslide density compared to the entire study area, (c) Arithmetic mean of the general slope angle and (d) Landslide rate (Ratio of slide sample points to non-slide sample points)

Lithological Unit	a) Sampled points	b) Landslide density	c) Mean slope angle	d) Landslide rate
	%	%	°	%
Alluvial deposits	11.3	0.5	3	0.04
Debris	1.6	2.1	17	1.25
Loess, Loam	4.3	4.1	5	0.93
Landslide deposits	0.5	2.3	17	4.25
Quaternary fluvial terrace	13.4	3.7	4	0.26
"Wr. Becken" (Sand, gravel)	12.4	0.4	3	0.03
Molasse Zone (Clastic Sediments)	7.4	3.4	7	0.45
"Schlier" (Clay, Silt)	2.0	10.2	7	5.15
Flysch Zone (Sandstone, Marl)	18.3	61.8	14	3.34
Klippen Zone (Clay, Marl)	0.9	6.4	16	7.69
N. Calc. Alps (Dolomite)	17.9	2.9	25	0.15
N. Calc. Alps (Limestone with marls)	7.2	1.8	20	0.71
Bohemian Masif (Granite)	2.7	0.5	14	0.19

resolution. The land cover grid was reclassified from ten classes (coniferours forest, mixed forest, deciduous forest, arable land, pasture, rough pasture, snow&ice, debris, fallow land and settlement) to five classes: “Forest”, “Arable & Fallow Land”, "Pasture", "Settlement" and "Snow, ice, debris".

The landslide data, which gives the dependent variable for the modeling, is comprised of point data that was mapped on derivatives of the ALS DTM (Hillshade maps with different azimuth angles (315°, 45°, 135°), contour lines with a spacing of 4m and slope angle maps) The landslides were detected visually on the hillshade and orthophoto imagery by interpreting and identifying the specific morphology that landslides leave after occurring (i.e. concave main scarp, convex accumulation zone, significant changes in slope angle and visible fissures or cracks). One point was set in the main scarp area at each detected landslide because there the landslide boundaries are easy to detect what results in high relative accuracy in the location of the points (Van Den Eeckhaut et al. 2006). Furthermore tests with different types of inventory data showed that using points in the main scarp still results in satisfactory evaluation values and susceptibility maps (Petschko et al., in press).

The following grids were derived from the DTM and were obtained by the respective SAGA modules: aspect angle, slope angle, topographic wetness index (SAGA wetness index, see Boehner et al. 2002), catchment height, catchment slope angle, catchment area, curvature, horizontal curvature and vertical curvature. Additionally curvature was derived with different window sizes in order to analyze which variables characterize the morphology and the present landslide distribution best. This datasets were computed in GRASS GIS applying the module r.param.scale (Wood 1996) with a rectangle size of nine pixels (profile curvature, planar curvature and maximum curvature, as defined by Wood 1996).

4.2 *Analysis of heterogeneity/homogeneity zones*

The heterogeneity of the study area mainly results from the different morphology that is strongly connected to a change in lithology and geotechnical characteristics. This was analyzed in more detail by four methods to show the differences between the lithological units: (1) a visual interpretation of the hillshade map overlain with the lithological map was performed. (2) This visual interpretation was analyzed in more detail by an exploratory comparison of mean slope angle in each lithological unit. (3) The distribution of landslides according to slope angle was tested with spineograms plotting slope angle with landslide/no landslide points for each lithological unit. (4) Another indication of the heterogeneity of the area might be the selection of different explanatory variables for each lithological unit when fitting a model with stepwise variable selection (see 4.3). This would reflect differences in the predisposing factors to landslides of each lithological unit. Therefore the count of selection of each variable in the models for all 13 lithological units was analyzed.

4.3 *Modeling with generalized additive models*

The analysis of the heterogeneity/homogeneity zones showed that besides the geotechnical characteristics also the mean slope angle changes in most cases with changes in the lithological unit. For the modeling and our study design this has the following implication: to model this relationship between slope angle and lithological unit correctly, the implementation of an interaction term is needed that describes this relationship exactly (Hastie & Tibshirani 1990, p.264). As the lithological units describe major changes in geotechnical characteristics of the material our proposed study design is to fit a GAM (R package "gam" described by Hastie 2006) for each lithological unit instead of for the entire study area.

The sample points for the modeling were merged out of two datasets: (1) sample points that were selected randomly in the area outside of landslides with a density of 2% of all grid cells of the test study area (408,918 points) and (2) all mapped landslide points (4055). Subsequently the values of all explanatory grids were extracted to this merged "original sample" to derive a data frame with all information on explanatory and dependent variables. To facilitate the modeling in the lithological units this "original sample" was split according to the extent of the lithological units and the "landslide rate" showing the ratio of original sample points storing information on "slides" to points storing information on "no slides" was obtained. From these new samples respective subsamples were selected according to a relation 1:1 (slides:no slides). With this subsamples a GAM was fitted for each lithological unit. For fitting the models we used a combined backward and forward stepwise variable selection in R based on Akaike's Information Criterion (AIC, Akaike 1974). The AIC can be applied to automatically determine the best fit of variables for a model as it evaluates the significance of the variables and penalizes for model complexity. During the stepwise variable selection the following choices of using the variable in the model are made and tested by the GAM (Hastie 1991): (1) omitting the variable, (2) use the variable linearly and (3) use the variable with a smooth function which is estimated nonparametically. By comparing the resulting AIC for each model fitted with different variable selections, the GAM decides on the model with the best combination of variables. For the curvature all variables derived with window sizes of three and nine pixel were put at choice. Furthermore, slope was made available once as general slope angle and once as catchment slope angle.

4.4 *Validation with AUROC*

In general a statistical validation provides a comparison of the modeled susceptibility with the present location of landslide points. The resulting susceptibility maps of the lithological units were validated by the calculation of the area under the receiver operating curve (AUROC, Hosmer & Lemeshow 2000). The ROC curve plots all combinations of sensitivities (percentage of correctly classified landslide points) against the false-negatives (percentage of wrong classified non-landslide points). Then the area under this curve is calculated which results in values between 0-1. Values form 0-0.5 show that the model could not discriminate between slides and no slide points whereas a value of 1 shows perfect discrimination (Brenning 2005). This calculation is facilitated by creating a test data set additionally to the training data set that was used for fitting the model. More details on this method can be found in Brenning (2005) and Begueria (2006).

5 RESULTS & DISCUSSION

5.1 *Data preparation*

A total of 4055 main scarps of slides were identified for the study area by mapping the landslides on basis of the ALS DTM derivatives. The landslide density and landslide rate of each lithological unit is presented in Table 1 (b) and d)).

5.2 *Analysis of heterogeneity/homogeneity zones*

The visual interpretation showed that with the change of the lithological units also the morphology changes distinctly. The results of exploratory analysis showed significant differences of the mean slope angle in most lithological units, although few units have similar mean slope angles (Table 1 c)). The Flysch Zone, for example, has a mean slope angle of 14° which is 11° lower than the mean slope angle of about 25° of the Dolomites of the Northern Calcareous Alps. In the resulting spineograms (Fig. 2) the proportion of landslides to no landslides according to the detected slope angle is plotted taking into account the relative area of the respective slope unit which is shown by the width of the bars. Therefore you can identify at which slope angle most of the landslides occurred and how this proportion evolves with rising slope angles. Comparing for example the Flysch Zone with the Dolomites we see that in both units more landslides (proportion larger than 50%) occurred starting from a slope angle of 15°. While in the Flysch the proportion of slides to no slides rises with increasing slope angles in the Dolomites this proportion drops below 50% at a slope angle of 30°. In general, flat areas with up to 5° show percentage of landslides close to zero. However, the zones of “Loess & Loam”, “Molasse” and “Schlier” 5-10% of landslides occurred at these slope angles up to 5°, which has also been recognized during field work. Furthermore in the usually flat lithological units “Alluvial deposits” and the “Wr. Becken (Sand, Clays)” the spineograms show mapped landslides and slope angles of up to 25°. This high slope angles may occur along roads, where the slope was steepened artificially, or at deeply incised streams as we saw in the field at the river Ybbs. Additionally it may be related to some uncertainties in the delineation of the zones in the original geological map.

The results of the fourth method to analyze the heterogeneity are presented in the modeling section.

5.3 *Modeling with generalized additive models*

The original rate of “slide” to “no slide” sample points is presented in Table 1d (Landslide rate) and shows especially in the “Klippen”, “Schlier”, “Landslide” and “Flysch Zone” a high landslide rate. The other units, particularly the “Alluvial deposits” and the “Wr. Becken (Sand, gravel)” show a comparably low landslide rate. Besides showing the differences in the relative landslide susceptibility of each unit, this emphasizes that there is a different effect of reducing the original sample to a subsample with a ratio of 1:1. This has to be considered at producing the resulting susceptibility maps to ensure the comparability of the lithological units.

Table 2 shows the counts of selection of each variable with a possible maximum count of 13. The total numbers show, that the variable slope angle was used in the model of 11 lithological units. The topographic wetness index was selected in seven of the models mostly in a smoothed form (four out of seven models). Horizontal curvature and catchment aspect have been used in 6 lithological units while profile and planar curvature have never been selected. This table emphasizes that for each lithology different variables have been selected either in their normal linear (“Sum N”) or in using a smooth function transforming the variable (“Sum S”).

5.4 *Validation with AUROC*

The AUROC value was calculated for the susceptibility map of each lithological unit after fitting a model respectively, where the best combination of variables was determined according to the AIC. The resulting AUROC values show the quality of the respective best fit model. The comparison of the AUROC values shows eleven units having AUROC values between 0.66 and 0.95. The highest AUROC value has the unit “Wr. Becken (Sand, Gravel)” with 1 whereas the lowest AUROC value was calculated for the unit “Dolomite” with 0.55. According to these results we state that in each lithological unit the model was able to discriminate between slide and no slide points successfully. However, there are differences in the performance. This is related to the different landslide sample size in each of the units. Especially at very small sample sizes the model tends to overfit (AUROC = 1), which means that the model fits too closely to the present data and is less capable of capturing minor fluctuations in the data.

Table 2: Results of stepwise variable selection. The numbers represent the count of usage of each variable in the 13 models for different lithological units. "Sum N" = variable used linearly, "Sum S" = variable is used with a smoothing function, "Total" shows the total count of usage. n.a. = not applicable.

Variable	Sum N	Sum S	Total
Slope angle	11	0	11
Catchment slope angle	1	0	1
Catchment area	1	2	3
Catchment height	2	1	3
Catchment aspect	1	5	6
Curvature	1	3	4
Horizontal curvature	5	1	6
Vertical curvature	4	0	4
Profile curvature (9)	0	0	0
Planar curvature (9)	0	0	0
Maximum curvature (9)	4	0	4
North (Aspect)	1	0	1
East (Aspect)	2	0	2
Arable & Fallow Land	4	n.a.	4
Pasture	4	n.a.	4
Snow, ice, debris	2	n.a.	2
Settlement	2	n.a.	2
Topographic wetness index	3	4	7

6 CONCLUSIONS

Within this study we have shown the details on the differences of the lithological units regarding geotechnical characteristics and also the morphology (which was described by analyzing the mean slope angle). The visual comparison of the hillshade map and the lithological map showed that the lithological map gives an acceptable good delineation of the morphological units. More details on the heterogeneity of the test study area were shown by the results of the exploratory analysis of the slope angle for each lithological unit and interpretation of the spinegrams of landslide occurrence and slope angle. According to the findings there we conclude that there are some uncertainties in the delineation of the lithological units but still they give very important information on different geotechnical characteristics.

According to the findings in the analysis of the heterogeneity we propose that in our study design it is necessary to fit a model for these units respectively. In order to avoid the usage of interaction terms to guarantee for an easier interpretation of the model for the stakeholders, and to still be able to give a good characterization of the study area on the aimed output scale, we decided to fit one GAM for each of these lithological units. The results show that with the GAM a model can be fitted for each lithological unit with a resulting AUROC value, which shows a good ability of the model to discriminate between slide and no slide points. However, some units may be affected by low number of landslide samples which has to be analyzed in more detail. Especially when switching to modeling the entire province of Lower Austria this effect may probably change or disappear. The analysis showed that we may consider merging lithological units with similar mean slope angles when the geotechnical characteristics are similar as well. Furthermore it should be considered to integrate the units debris and landslides in their surrounding units. This has to be analyzed in more detail for the application in Lower Austria.

The results of the variable selection for each unit show that different variables were selected for the model of each lithological unit while only the variable slope angle was used in nearly every model. This supports the hypothesis that each lithological unit may be characterized best by different predisposing factors. This in turn emphasizes the necessity to fit a model for each lithological unit in order to give the best characterization regarding landslide susceptibility in the province of Lower Austria.

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8 REFERENCES

Aleotti, P., Chowdhury, R., 1999. Landslide hazard assessment: summary review and new perspectives. *Bulletin of Engineering Geology and the Environment* 58: 21-44.

Akaike, H., 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control, 19(6), 716-723.

Atkinson, P., Jiskoot, H., Massari, R., Murray, T. 1998. Generalized linear modelling in geomorphology. *Earth Surface Processes and Landforms* 23(13): 1185–1195.

Atkinson, P. & Massari, R. 2011. Autologistic modelling of susceptibility to landsliding in the central apennines, Italy. *Geomorphology* 130(1-2): 55-64.

Beguería, S. 2006. Validation and Evaluation of Predictive Models in Hazard Assessment and Risk Management. *Natural Hazards* 37(3): 315-329.

Bell, R. 2007. Lokale und regionale Gefahren- und Risikoanalyse gravitativer Massenbewegungen an der Schwäbischen Alb. *Dissertation thesis*, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany.

Bobrowsky, P.T. & Domínguez-Cuesta, M.J. 2011. A proposed landslide susceptibility map of Canada based on GIS. In F. Catani, C. Margottini, A. Trigila & C. Iadanza (eds), *The second World Landslide Forum – Abstract Book*: 280. Italy: ISPRA.

Boehner, J., Koethe, R. Conrad, O., Gross, J., Ringeler, A., Selige, T. (2002): Soil Regionalisation by Means of Terrain

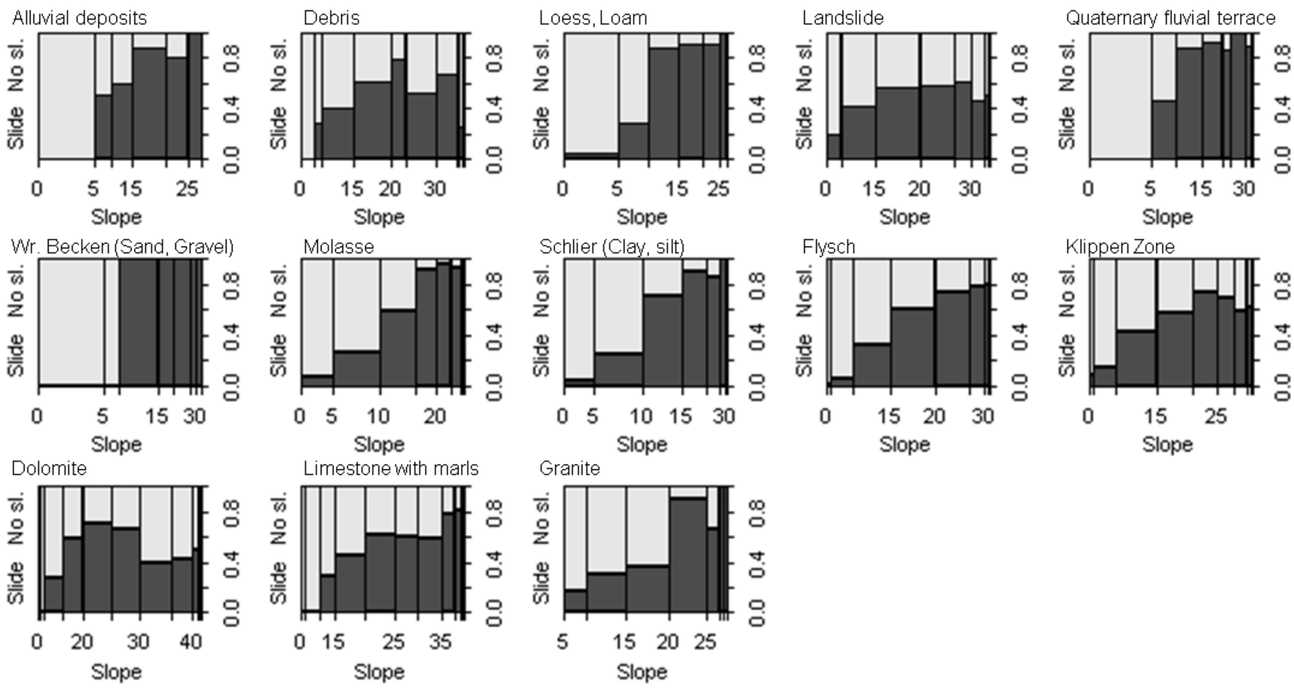

Figure 2. Spineograms for each lithological unit showing the relation of slide / no slide points for the respective slope angle.

Analysis and Process Parameterisation. In: Micheli, E.,Nachtergaele, F., Montanarella, L. [Ed.]: Soil Classification2001. European Soil Bureau, Research Report No. 7, EUR 20398 EN, Luxembourg. pp.213-222.

Brenning, A. 2005. Spatial prediction models for landslide hazards: review, comparison and evaluation. *Natural Hazards and Earth System Sciences* 5: 853–862.

Brenning, A. 2008. Statistical Geocomputing combining R and SAGA: The Example of Landslide susceptibility Analysis with generalized additive Models. SAGA—Seconds Out, *Hamburger Beiträge zur Physischen Geographie und Landschaftsökologie* 19: 23-32. Germany.

Dikau, R. & Glade, T. 2003. Nationale Gefahrenhinweiskarte gravitativer Massenbewegungen.- In: Liedtke H., Mäusbacher R. & Schmidt K.-H. (eds.), *Relief, Boden und Wasser.- Nationalatlas Bundesrepublik Deutschland*: 98-99. Institut für Länderkunde, Leipzig.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W. Z., & on behalf of the JTC-1 Joint Technical Committee on Landslides and Engineered Slopes, 2008. Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. *Engineering Geology* 102(3-4): 99–111.

Ferentinou, M. & Chalkias, C. 2011. Mapping Mass Movement Susceptibility across Greece with the use of GIS, Artificial Neural Network and Statistical Methods. In F. Catani, C. Margottini, A. Trigila & C. Iadanza (eds), *The second World Landslide Forum – Abstract Book*: 91. Italy: ISPRA.

Glade, T. & Crozier, M.J. 2005. A review of scale dependency in landslide hazard and risk analysis. In: Glade, T., Anderson, M. & M. Crozier (eds): *Landslide hazard and risk:* 75-138. Chichester.

Goetz, J.N., Guthrie, R.H., Brenning, A. 2011. Integrating physical and empirical landslide susceptibility models using generalized additive models. *Geomorphology* 129: 376-386.

Günther, A., Reichenbach, P., Malet, J.-P., Hervás, J., Foster, C., Van Den Eeckhaut, M. & Guzzetti, F. 2011. New developements in harmonized landslide susceptibility mapping over Europe in the framework of the European Soil Thematic Strategy. In F. Catani, C. Margottini, A. Trigila & C. Iadanza (eds), *The second World Landslide Forum – Abstract Book*: 100. Italy: ISPRA.

Hastie, T.J. & Tibshirani, R. 1990. Generalized additive models, Chapman & Hall/CRC, London.

Hastie, T. J. 1992. Generalized additive models. In Chambers, J.M. & Hastie, T.J., S*tatistical Models in S.* Wadsworth \& Brooks/Cole.

Hervas, J. (ed.) 2007. Guidelines for Mapping Areas at Risk of Landslides in Europe. Proceedings of the Experts Meeting held on 23-24 October 2007. Institute for Environment and Sustainability Joint Research Centre (JRC), Ispra: Italy.

Hosmer, D.W. & Lemeshow, S., 2000. Applied logistic regression, John Wiley & Sons, New York, 2.nd edn., 373 pp..

Jia, G., Yuan, T., Liu, Y., Zhang, Y., 2008. A static and dynamic factors-coupled forecasting model or regional rainfall-induced landslides: a case study of Shenzhen. *Science in China, Series E: Technological Sciences* 51, 164–175.

Park, N.W., Chi, K.H., 2008. Quantitative assessment of landslide susceptibility using high-resolution remote sensing data and a generalized additive model. *International Journal of Remote Sensing* 29, 247–264.

Petschko, H., Bell, R., Leopold, P., Heiss, G., Glade, T. In press (2011). Landslide inventories for reliable susceptibility maps. In F. Catani, C. Margottini, A. Trigila & C. Iadanza (eds), *The second World Landslide Forum –Proceedings*. Italy: ISPRA.

Soeters, R., van Westen, C.J., 1996, Slope instability recognition analysis and zonation, In Turner, K.T & R.L. Schuster (eds), *Landslides: Investigation and Mitigation*. Transportation Research Board National Research Council, Special Report 247: 129-177. Washington D.C.

Trigila, A., Casagli, N., Catani, F., Crosta, G., Esposito, C., Frattini, P., Iadanza, C., Scarascia Mugnozza, G., Segoni, S., Spizzichino, D., Tofani, V. 2011. Landslide susceptibility mapping at national scale: the Italian case study. In F. Catani, C. Margottini, A. Trigila & C. Iadanza (eds), *The second World Landslide Forum – Abstract Book*: 158. Italy: ISPRA.

Van den Eeckhaut, M., VanWalleghem, T., Poesen, J., Govers, G., Verstraeten, G., Vandekerckhove, L. 2006. Prediction of landslide susceptibility using rare events logistic regression: A case-study in the Flemish Ardennes (Belgium).- *Geomorphology* 76(3-4): 392-410.

Wood, J. 1996. The Geomorphological characterisation of Digital Elevation Models. Dissertation, Department of Geography, University of Leicester, U.K.