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ADVANCED METHODS FOR LANDSLIDE ASSESSMENT USING GIS

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Contents / Obsah

Abstract

This thesis considers various modeling approaches for assessment of landslides, ranging from heuristic (expert-based), statistic and deterministic (physical-mathematical) to advanced methods. The latter included various state-of-the-art Machine Learning techniques, based on training/testing protocols, which makes them fundamentally different from the other abovementioned approaches. Landslide assessment involved two aspects: modeling of landslide susceptibility (defined throughout the area by low-high susceptibility values) and spatial prediction of landslides. To achieve this task the following main principles applied: (i) landslide occurrences are in relation with the Conditioning Factors (various terrain properties), (ii) similar conditions that have led to a landslide occurrence in the past will lead to its reoccurrence, (iii) similar conditions that have led to a landslide occurrence in some area will induce landslide occurrence elsewhere. Conditioning Factors are represented by morphometric, geological, hydrological/hydrogeological and environmental properties of the area, given as various thematic layers in GIS. These represented the input dataset which has then been appropriately processed and together with the available Landslide Inventory fed to the according modeling procedure. The model retrieved susceptibility and/or prediction of landslides throughout the area. It is compared against the available Landslide Inventory for its final evaluation. Three different case studies have been investigated, similar enough, yet different enough to challenge the advanced modeling techniques. The first regarded Fruška Gora Mountain in Serbia with deep-seated earth slides; the second, Starča Basin in Croatia, with shallow earth slides; and the third, Halenkovice area in Czech Republic, with earth slides/flows in characteristic flysch formations. It has been shown that Machine Learning methods, particularly SVM (Support Vector Machines) are the most suitable for landslide susceptibility modeling, since the most of these models performed extremely well. When it comes to landslide prediction, the results are somewhat ambiguous, since some models performed very well, while the others did not meet the expected accuracy. In conclusion, the proposed methodology produces acceptable susceptibility models that could be applied in urban/regional planning, disaster management/mitigation, hazard/risk analysis, while the models of landslide prediction have limited applicability in landslide mapping and perhaps different levels of planning.

Keywords: landslides, landslide susceptibility, modeling, GIS, Machine Learning

1. Intoduction

Landslides stand among the most widespread natural hazards, hand-in-hand with earthquakes, volcanoes, floods and storms, which are usually linked, i.e. preceded or followed by landslides. The latest research (Petley 2012) has shown that there is a rising toll of landslide casualties, most likely due to the expansion of the global population and widening of the human interaction with the geological environment. This life and property threatening phenomenon has thus attracted the public and academic communities, world-wide. Given such motifs, the landslide investigations have been rising exponentially in the past decade (Gokceoglu & Sezer 2009), and this research could be enlisted as a follower of such trend. The rise has been further stimulated by the simultaneous developments in the field of technology, computer science and GIS, diversifying the methodology and increasing the accuracy of landslide assessment. At present, the state-of-the art techniques, such as advanced Machine Learning algorithms, are being implemented at unprecedented scales, giving valuable interpretations and predictions, which are applicable in the mitigation of the landslide, and other natural hazards. It is important that the landslide assessment is developing within a certain framework, endorsed by the leading communities (Engineering Geology, Geomorphology, Geotechnics, Geophysics, etc.). Its purpose is to define and systematize the terminology and methodology of research, so that the independent researches and experiences can be compared. That is the only way to improve the knowledge on landslides, their behavior, mechanisms, triggers, aftermath etc. This research is following the guidelines of the leading communities in terms of nomenclature and methodology, although it is the author's intention to propose/promotes some specific assessment techniques.

In the context of the landslide assessment framework which has been complied throughout this thesis as a standard, several basic terms should be pre-defined:

- landslide is any downward movement of rock, debris or earth mass,
- susceptibility is a spatial probability of the landslide occurrence,
- landslide classification is defined by a standard one (Varnes 1984).

Finally, it should be mentioned that the landslide assessment rests on the following basic principles:

- landslides are caused by the interplay of ground conditions or Conditioning Factors and Triggering Factors,
- landslides will reoccur when and where these conditions are met.

2. Objectives

Resting on the abovementioned motifs, this research was shaped to meet the standardized requirements in terms of methodology of data acquisition and manipulation, choices of the advanced modeling approaches for landslide assessment, as well as the model evaluation techniques, and finally, the visualization choices, all via GIS (WP/WLI 1995, Turner & Shuster 1996, Fell et al. 2008, Lynn & Bobrowsky 2008, Gerath et al. 2010, Brenning 2012). These are to be realized by following the thesis objectives systematized as follows.

1. Exploiting only low-cost data resources (available or open-source topographic, geological, satellite imagery and other repositories) and open source software packages.
2. Inspecting of the phenomena from different case-studies, including similar, but sufficiently different terrains (in order to compare the modeling results and test the capabilities of proposed methodological solutions).
3. Standardizing the data acquisition regarding the data type, scale, preprocessing procedures and so forth (in order to have fully comparable models from different case-studies) using GIS.
4. Implementing a variety of well-known modeling approaches, but also experimenting with the state-of-the-art techniques, advanced methods and unprecedented solutions for landslide assessment using GIS. Resulting models are to present transient relative values over the area, pinpointing landslide-endangered zones and safe zones (which shall be further elaborated).
5. Evaluating the results, i.e. the models performance in the most appropriate fashion, obtaining qualitative and quantitative descriptors of the models performance using GIS in combination with statistical tools.
6. Visualizing and publishing the results in the form of generic maps per each case-study using GIS, and Web-GIS and estimating their applicability.

3. Methods

Various methods have been used in different stages of this research, ranging from data preparation methods, landslide assessment methods and model evaluation methods, so they will be structured accordingly.

Data preparation included various techniques for ordering and formatting data to meet the requirements of specific landslide assessment methods. Among the other, standard procedures (ranging, normalization, binarization etc.), Attribute Selection methods have been included. They have been used primarily to ensure the choice of the input Conditioning Factors, by ranking via *Information Gain* and *Chi-Square* techniques. However in the last two case studies, particularly in the last one (Halenkovice area in Czech Republic) Attribute Selection have had a wider purpose. Therein, *Information Gain* was used for ranking of Conditioning Factors in leave-one-out learning protocol. In addition all Machine Learning-based models have required splitting of the dataset into training and testing part, using different sampling strategies.

The group of landslide assessment methods included various methods ranging from heuristic, statistic and deterministic to more advanced - Machine Learning techniques:

- Analytical Hierarchy Process (AHP) – a simple GIS-integrated expert-based method (Saaty 1980),
- Conditional Probability, with Weight of Evidence technique – a simple statistical method (Bonham-Carter 1994),
- Fuzzy Logics model - based on different membership functions, with multiple levels and multiple fuzzy operators (Zadeh 1965),
- *Stability Index* (*SI*) model – a simple GIS-integrated deterministic method (Peck 2001),
- *k*-NN – semi-supervised Machine Learning classifier (Mitchell 1997),
- C4.5 Decision Tree – supervised Machine Learning classifier (Quinlan 1993),
- Logistic Regression – supervised Machine Learning classifier (Varmuza & Filzmoser 2009),
- Support Vector Machines (SVM) – supervised Machine Learning classifier (Kanevski et al. 2009).

The evaluation methods have been based on various estimators based on confusion matrix, i.e. on estimating performance on the basis of *True Positives*, *True Negatives*, *False Positives* and *False Negatives* relations. One of the most important methods included ROC (Receiver Operating Characteristics) curves which allow quantitative (based on the *AUC* parameter – *Area Under Curve*) and qualitative (based on the curve features) estimation of modeling performance (Fawcett 2006).

All these methods have been applied at according stages of the modeling procedure (Fig. 1), but there have been slight differences in the modeling procedure. Firstly, the data that were required for deterministic models have included geotechnical parameters, which have had to be optimized and regionalized. Secondly, non-Machine Learning methods required ranged numeric Conditioning Factors (inputs had to be ranged in arbitrary intervals) and nominal Conditioning Factors had to be scored (each class was allocated with a 0–100 score, depending on the factor's estimated influence on landslide occurrence). On the other hand, Machine Learning techniques required normalization of numeric, binarization of categorical inputs, and in some cases, ranking of the inputs based on Attribute Selection. The modeling procedure also differed in respect to the model type. Landslide prediction models have been implemented directly after their optimization (discrete Machine Learning classifier implementation). Landslide susceptibility models have required either iterative implementation succeeded by averaging and normalization (Machine Learning-based susceptibility models), either direct (quasi-)probability scoring (AHP, Weight of Evidence and Fuzzy models).

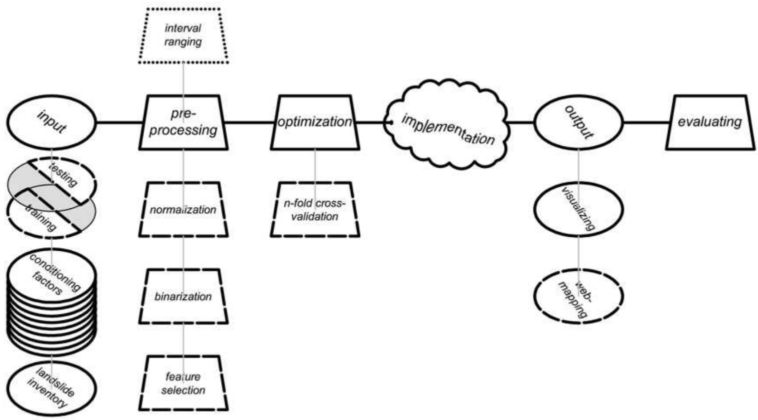

Fig. 1. Research workflow (dashed elements apply only for Machine Learning models, while dotted elements only for conventional models).

4. Results

As mentioned before, three case studies have been elaborated in this research. Pilot area of the first case study has been researched the longest and all proposed methods have been tested, while in the other two case studies, only the selected methods were particularized.

a. Case study 1 - Fruška Gora Mountain (Serbia)

The case study encompassed NW slopes of Fruška Gora Mountain (Serbia), characteristic for its deep-seated earth-slides hosted in Neogene basin formations (primarily clay and marl formations). The most of the landslides are seated along the Danube's right riverbank, making a river erosion one of the principal landslide triggers, together with heavy rainfall events and exceptionally earthquake events (not that common for this area).

The dataset comprised of several thematic layers representing various Conditioning Factors (formatted as 2D raster grids) and the Landslide Inventory (obtained by a combination of field and Remote Sensing-based mapping). The Conditioning Factors have included the following:

- morphometric data: *elevation*, *slope angle*, *aspect*, *slope length*, *plan* and *profile curvature*;
- hydrological/hydrogeological data: *distance from stream*, *Topographic Wetness Index* (*TWI*);
- geological data: *lithology*, *distance from structures*, *distance from hydrogeological boundaries*;
- environmental data: *vegetation cover* (reclassified *NDVI*).

Apart from these, some geotechnical data have been used for deterministic modeling (cohesion, friction angle, bulk density etc.).

The resulting models ranged from simple to advanced models, based on Machine Learning techniques. They have been named and numbered accordingly, and some of them have several variants which have also been accordingly denoted.

Model-1a (Fig. 2a) is a landslide susceptibility model that had implemented AHP method through several variants. In each variant, the input Conditioning Factors have been pair-wised and arbitrarily scored. The final model is obtained by averaging these scores, and according to the evaluation metrics, the model turned viable (*AUC*=0.78 and balanced ROC curve).

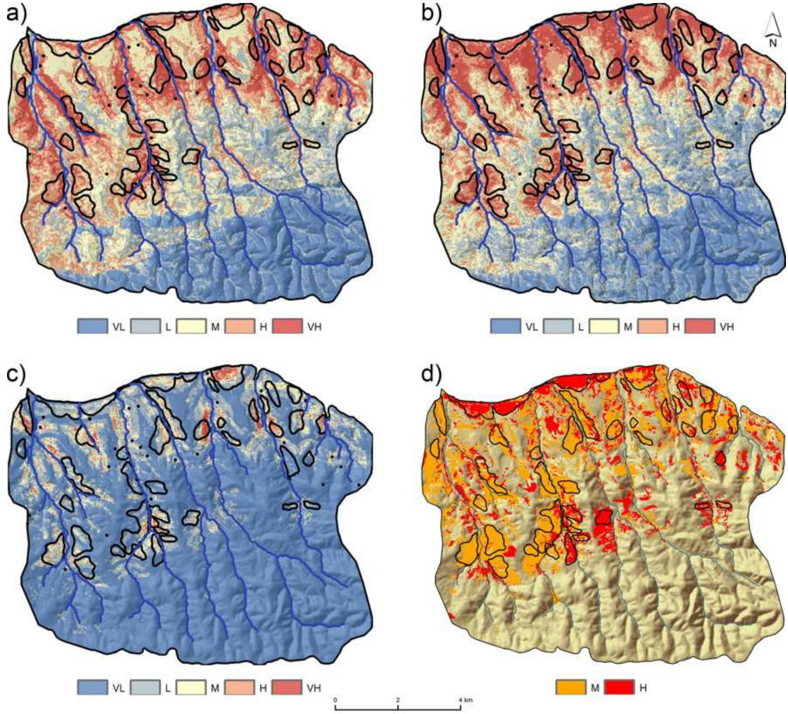

Fig. 2. Various models from the first case study
(VL=Very Low susceptibility, L=Low susceptibility, M=Moderate susceptibility=Dormant landslides, H=High susceptibility, VH=Very High susceptibility=Active landslides).

Model-2a (Fig. 2b) is a landslide susceptibility model that had implemented Weights of Evidence technique. It had slightly better performance than previous model (*AUC*=0.85) and similar character of the ROC curve.

Model-3a (Fig 2c) is also a landslide susceptibility model that had implemented Fuzzy technique, based on two variants of membership functions (Cosine Amplitude and Frequency Ratio). It has been separated on two levels and fuzzy gamma operator (γ=0.5) has been chosen for final combination of sub-models. The performance of the best model variant was similar to the previous model (*AUC*=0.82), with slightly better qualitative evaluation of the ROC curve, because it turned more conservative, thus provided a safer model.

Model-4a is a landslide susceptibility model that had implemented *k*-NN technique, but has not met the expectation and returned poor results.

Model-5a (Fig 2d) is a landslide prediction model that had implemented C4.5 Decision Tree classifier. It had performed very well (*AUC*=0.82) in all variants with balanced and reduced sampling strategy (variant Model-5a-B-10%).

Model-6a (Fig 3a) is also a landslide prediction model that had implemented Logistic Regression classifier. Its best performance was also in the variants with balanced reduced sampling (Model-6a-B-10%), but the obvious overestimations of landslides (*False Positive* errors) troubled this model.

Model-7a had both variants, a landslide susceptibility (Fig 3b) and prediction model (Fig 3c), that both have implemented the SVM classifier. The susceptibility model performed extremely well (*AUC*=0.95) while predictive model was only plausible (*AUC*=0.71).

Model-8a (Fig 3d) is a landslide susceptibility model that had implemented *SI* deterministic concept. It underperformed (*AUC*≈0.5) as expected, because it is rather convenient for shallow than deep-seated landslides.

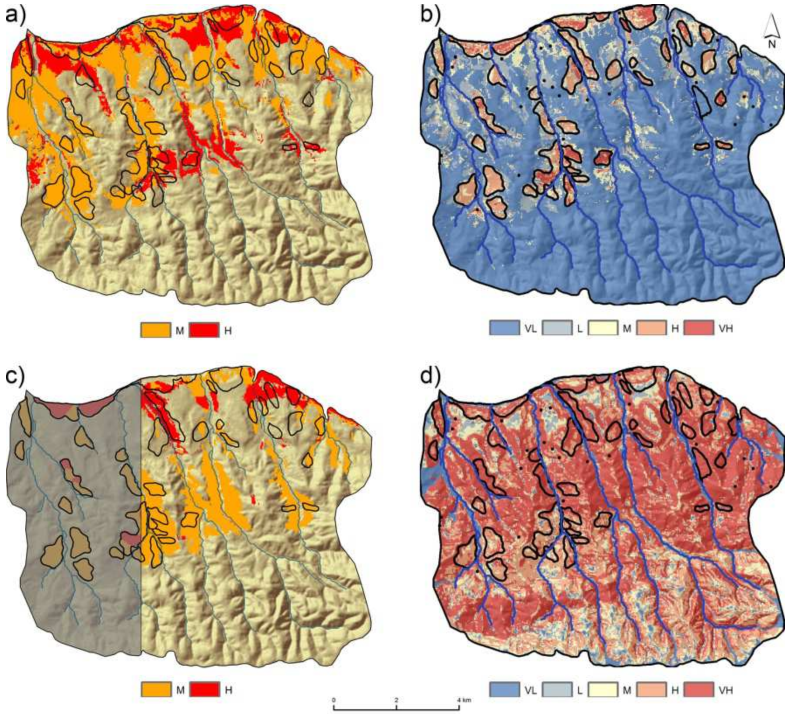

Fig. 3. Various models from the first case study (continued).

b. Case study 2 - Starča Basin (Croatia)

The second case study encompassed western outskirts of Zagreb City (Croatia), with typical shallow earth-slides developed in a Neogene basin (dominated by clay, marl and sand formations), where rainfall appears to be the principal trigger.

The dataset also comprised of several Conditioning Factors and the Landslide Inventory (obtained by a field-based mapping). The Conditioning Factors have included the following:

- morphometric data: *slope angle*, *slope length*, *downslope gradient*, *aspect*, *plan curvature, profile curvature*, *convergence index*, *LS factor*, *channel base elevations*, *altitude above channels*;
- hydrological/hydrogeological data: *Stream Power Index* (*SPI*), *TWI, groundwater depth*;
- geological data: *lithology*, *distance from structures*;
- environmental data: *Land Cover*.

Only selected models that have proven successful in the previous case study have been implemented (only Machine Learning-based models). They all had at least two variants: the first was the landslide prediction model and the second was the predictive model which only regarded the classification of different landslide types. These variants have had their own sub-variants which had different training sampling (different size and strategy of the sampling).

Model-5b-1 is a landslide prediction model that had implemented C4.5 Decision Tree classifier. It had not performed particularly well in neither of sub-variants.

Model-5b-2 is a landslide class prediction model, based on the same classifier as Model-5b-1, and had the same sub-variants. It performed well only in the sub-variants with the large sampling sizes (>20%).

Model-7b-1 is a landslide prediction model that had implemented SVM classifier, and also did not perform particularly well. However, one particular predictive model, labeled Model-7b-40% based on a manual sampling draws attention (Fig 4a). It has made plausible prediction (*AUC*≈0.6) with obvious underestimation of landslides (*False Negative* error dominates).

Model-7b-1 is also SVM-based landslide class prediction model. Its sub-variants with large training sample sizes have matched the performance of the according sub-variants of Model-5b-2.

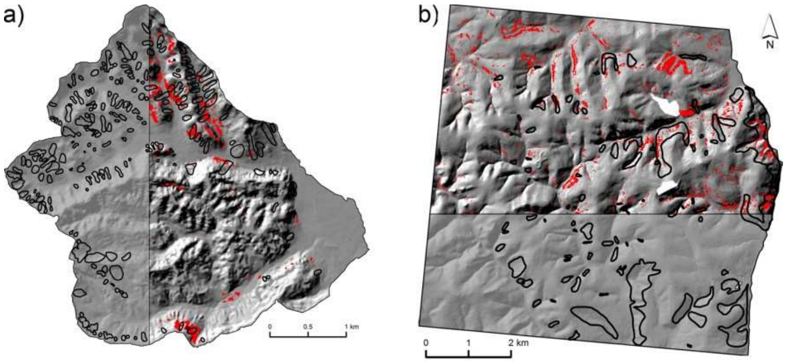

Fig. 4. Landslide prediction models from the second a) and third case study b) (training areas are shaded, actual landslides are contoured, landslide predictions are given in red color).

c. Case study 3 - Halenkovice area (Czech Republic)

The last case study regarded the wider area of Halenkovice town in Czech Republic. The geological setting is very typical, with its complex of flysch formations that host mostly shallow earth-slides and earth-flows, triggered mainly by heavy rainfall.

Again, the dataset comprised of several Conditioning Factors and the Landslide Inventory (obtained by a field-based mapping). The Conditioning Factors have included the following:

- morphometric data: *elevation*, *slope angle*, *downslope gradient*, *aspect*, *convergence index*, *plan curvature, profile curvature*, *LS factor*, *channel base elevations*, *altitude above channels*;
- hydrological/hydrogeological data: *TWI, distance from stream*;
- geological data: *lithology*;
- environmental data: *Land Cover*.

The data have also included regionalized geotechnical data for the deterministic model (cohesion, friction angle, bulk density etc.).

Only the SVM-based models and *SI*-based deterministic model have been implemented, because they seemed the most suitable. Nevertheless, this last case study is still under the investigation and some other models or the same models in their refined versions might follow in the future.

Model-7c-40% is a landslide prediction model that had implemented SVM classifier. The implementation was slightly unconventional and included leave-one-out learning protocol, where Conditioning Factors have been successively excluded from the learning dataset, starting from the last-ranked factor (according to the Attribute Selection ranking). The factor at which the model converged to a stagnant or decreasing performance was the last factor to be excluded from the learning dataset. The model (Fig 4b) turned out to be only plausible ($AUC \approx 0.6$), with obvious underestimation of landslides (*False Negative* error dominates).

Model-8c is a susceptibility model based on the *SI* deterministic concept. It actually performed much better than in previous case studies, especially in some parts of the area ($AUC = 0.62$).

5. Discussion

Advanced models, based on Machine Learning techniques, have proven their supremacy over more common approaches for a number of reasons. Firstly, they tend to perform much better in the case of landslide susceptibility models, when appropriate sampling strategy for training/testing is set. In all of the case studies it turned out that they easily outperformed conventional models. Their ROC curves tend to reach the peak performance with relatively low probability thresholds (Fig. 5), meaning that they give more conservative (safer) outputs. They have also shown a good generalization capacity when challenged with multinomial task (several landslide classes to discern). As for the second type of models, such as Model-7a-33%, Model-7b-40% and Model-7c-40%, the comment is not as straightforward. These are all predictive models, and since they are based on the training/testing protocols, they perfectly simulate potential scenarios (e.g. the situations in which an area does not have Landslide Inventory, but adjacent area does). Some of them have been very successful and very applicable (Model-7a-33%), while the others have been troubled with the overfit problem,for which several factors could be considered responsible. The algorithms learn too many wrong relations between *non-landslide* instances and the inputs, producing considerable amount of *False Negative* errors. It has been noticed that the Attribute Selection have had minor influence in preventing the overfit, so the key for avoiding it remains with the inventory and the training/testing sampling strategy. There are some improvements that might be applied directly (limiting the non-landslide class by some additional criteria) or indirectly (improving the results through the postprocessing filtering).

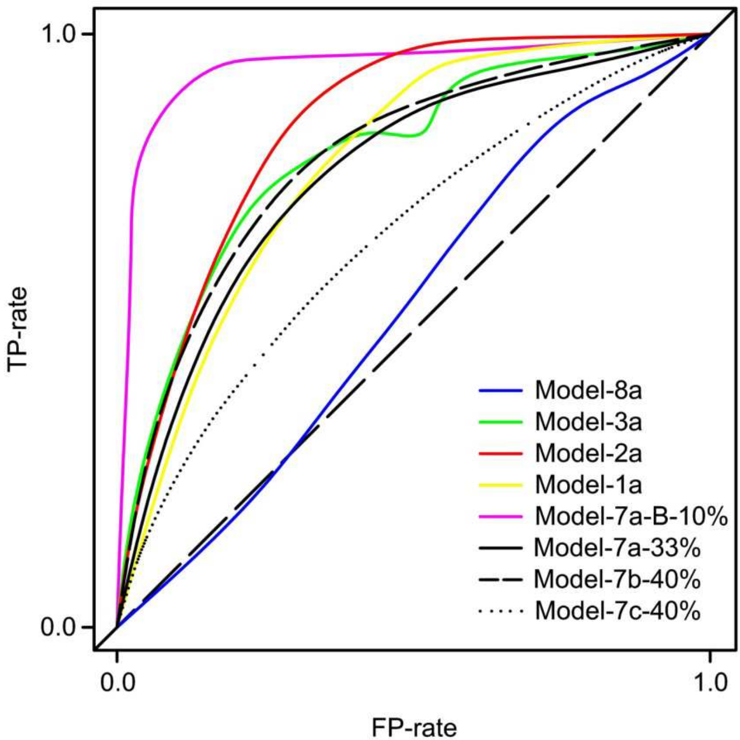

Fig. 5. ROC curve (performance) comparison.

It is further necessary to discuss the achievements of the thesis in relation to the objectives defined in Chapter 2.

In all of the case studies the data that have been used were obtained for free. Topographic information, CORINE classification maps, even geological maps, orthophotos and Landslide Inventories are freely available up to a certain scale. It is also the case of LANDSAT and other similar multispectral images. These scales turned sufficient for conducting proposed methodology and fulfilling the Objective 1. In addition, open source solutions, such as SagaGIS, MapWindow, Weka, R, MapComparisonKit and others, have been fully exploited in processing and modeling of these data, which utterly rounds-up the Objective 1.

Selected case studies have been somewhat similar, but still different enough to challenge the proposed methodology from different aspects. Therefore, it could be said that the Objective 2. has been consistently followed throughout this thesis.

Although the datasets did not contain exactly the same inputs, it is possible to perceive some standard pattern. It implies that each case study must have had several morphometric Conditioning Factors, and at least one hydrological, geological and environmental Conditioning Factor. Furthermore, all of the inputs underwent the same processing procedure, as demanded by applied methods. The only exception was with the deterministic models, which required specific (geotechnical) data inputs that have had to be arbitrarily adjusted within certain limits in order to suit the model. It could be inferred that the Objective 3 has been fully perceived throughout the thesis.

The first, pilot case study has been the most extensively elaborated, since there has been no similar investigation performed over this area before. Thus, the entire gamut of proposed methods has been involved, while in the last two case studies, the methods have been intentionally reduced to those which might have led to some new discoveries, which would supplement the previous investigations, conducted by other practitioners. In this sense, the fulfilling of the Objective 4 has been asserted.

The evaluation of the individual models in all of the case studies has been always given by several performance parameters, such as accuracy, several types of κ-indices, different error rates, ROC curves and AUC, all based on contingency tables (confusion matrices). Nevertheless, the evaluation of the modeling performance has remained problematic, especially for the predictive models, for a number of problems. The most appropriate method for model comparison turned out to be the ROC curve, because it allows qualitative and quantitative evaluation of the model. Objective 5 has thus been practically fulfilled.

Objective 6. has also been completed, since the visualization of the most of the models has been given by separate maps while some of the most interesting models have been additionally featured as interactive web-maps (Kilibarda & Bajat 2012):

http://milosmarjanovic.pbworks.com/w/file/fetch/63738284/MyMapFruskaGora.htm,

http://milosmarjanovic.pbworks.com/w/file/fetch/63741247/MyMapStarca.htm,

http://milosmarjanovic.pbworks.com/w/file/fetch/63739326/MyMapHalenkovice.htm.

6. Conclusion

This thesis rounds-off a detailed methodological proposal for mapping landslide susceptibility, by using some simple and advanced modeling methods. These have been tailored by the according research motifs and objectives, which have been consistently followed. The thesis is savored by three case studies on which the proposed methodology has been employed, tested and discussed. It outputs a dozen of different interpretable models, which have their drawbacks and benefits and different practical relevance.

The most significant drawbacks are seen in absence of GIS integration for advanced (Machine Learning) methods, which complicates the procedure of commuting the data to and from external Machine Learning standalone applications. Furthermore, the optimization and implementation of complex models can be very time-consuming. Another difficulty that was encountered regarded the plausibility of the evaluation measures for the predictive models.

As for the benefits and contributions of this research, the following has been concluded. The research has contributed by defining which models are the most reliable for susceptibility in general and also per particular case study, and the same apples for predictive models, even though the results in the latter case have not been straightforward. Another important benefit from the research was the proposition of the Conditioning Factor standardization and also the proposition of the optimal scale, i.e. optimal number of instances per case study.

The proposed methodology produces acceptable susceptibility models that could be applied in urban/regional planning, disaster management/mitigation, hazard/risk analysis, while the models of landslide prediction have limited applicability in landslide mapping and perhaps different levels of planning.

Further research is targeted in various directions. One is regarding the refinement of the input dataset by developing additional Conditioning Factors (geological domains, or data obtained by field measurements with satisfying sampling density). Another direction would be regarding the improving of the sampling strategy, by arbitrary logical limitations of the training set. Finally, the Machine Learning methods could be upgraded, wherein hybrid classifier approach is to be considered, as well as a combination of probabilistic and discrete classifiers (Tipping 2001).

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Shrnutí

Disertační práce řeší pokročilé metody předpovědí půdních sesuvů, od teoretických základů po konkrétní praktické příklady ve třech zájmových územích. Předmět výzkumu představuje velmi komplexní a heterogenní přírodní fenomén, jehož kvantitativní prognózy se obyčejně popisují náchylností, nebezpečím nebo rizikem. Autor klade důraz na náchylnost terénu ke klouzání, tj. prostorovou pravděpodobnost výskytu půdních sesuvů. Tento přistup vychází většinou z nedostatku vhodných časoprostorových dat potřebných pro analýzu nebezpečí nebo rizika. Na druhou stranu maximálně využívá všechna ostatní dostupná prostorová data, včetně geologických, geomorfologických, hydrologických, hydrogeologických a dalších dat o vlastnostech životního prostředí, která jsou v praxi často označována jako podmíněné faktory podmiňující půdní sesuvy.

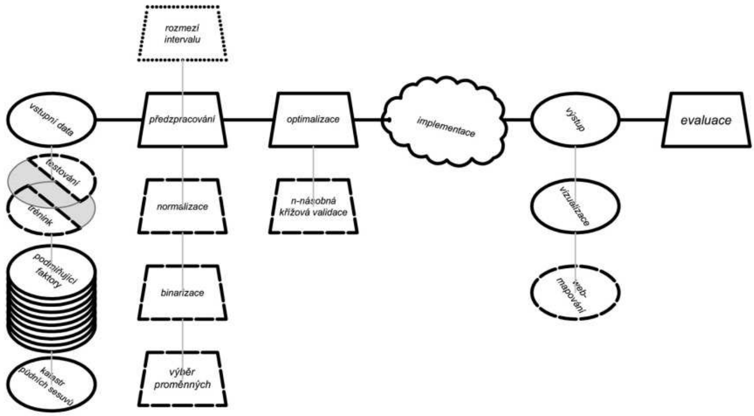
Hlavní cíle této disertace jsou:

1. použití dostupných, bezplatných dat a softwarových produktů s cílem prokázat, že využíváním stávajících dostupných zdrojů lze provést hodnotnou analýzu předpovědi půdních sesuvů,
2. testování původní metodologie v několika zájmových územích (navzájem dostatečně podobných, avšak i dostatečně rozlišných), aby bylo možné objektivně diskutovat o úspěšnosti navrhované metodologie,
3. standardizace vstupních dat z hlediska jejich objemu, typu, kvality a poměru, a jejich před-zpracování pomocí GIS,
4. použití řady metod modelování náchylnosti k půdním sesuvům, od jednoduchých až po pokročilé, s cílem je objektivně a podrobně porovnat,
5. použití co nejrelevantnějších metod pro evaluací modelů předpovědi sesuvů s cílem co nejobjektivnějšího kvalitativního a kvantitativního porovnaní těchto modelů,
6. vizualizace a publikování výsledků použitím GIS a prostředků webové kartografie.

Navrhovaná metodologie zahrnuje řadu metod, které lze rozdělit na metody předzpracování, modelování náchylnosti a metod hodnocení. Největší důraz byl kladen na metody modelování náchylnost k sesuvům půdy. Byly použity jak metody nejpopulárnější a nejjednodušší, tak i nejpokročilejší a nejsložitější metody, a to:

– heuristické (na základě subjektivní zkušenosti autora, který se zabývá problematikou sesuvů),
– deterministické (na základě známých fyzikálních principů týkajících se sesuvů půdy, které jsou do značné míry aproximovatelné),
– statistické (na základě statistické závislosti na vlastnostech různých vlastností terénu a sesuvů půdy),
– metody Strojového Včení (na základě logicky-matematicko-statistických algoritmů, které poloautomatický nacházejí vztahy mezi vlastnostmi terénu a projevy půdních sesuvů).

K poslední skupině patří metody k-nejbližší sousedství (nearest neighbor, k-NN), logistická regrese (LR), rozhodovací stromy (Decision Trees, DT) a Support Vector Machines (SVM), jejichž modely jsou předmětem disertační práce.



Obr. 1. Základní koncept výzkumu (přerušované prvky platí pouze pro modely Strojového Učení, zatím co tečkované prvky platí pouze pro konvenční modely)

Je potřeba zdůraznit, že autorem navržená metodologie (Obr. 1), která je stejným nebo podobným způsobem použitá ve všech třech zájmových územích a usilující o standardizaci, může být aplikována na zcela jiná území, která splňují určitá kritéria a mají k dispozici odpovídající údaje. Návrh metodologie začíná od problematiky výběru konkrétního typů (mechanismu) sesuvu, který je přítomen ve vybraných územích, dále pokračuje přes výběr vstupních dat o sesuvech půdy, která slouží jako podklad pro hodnocení modelu. Po definování základních kritérií metodika navrhuje použití řady metod pro předzpracování, modelování náchylnosti a/nebo predikci sesuvů, po kterém následuje představení, evaluace a srovnávaní výsledků. Závěrem metodologie vrcholí v diskusi o výhodách a nevýhodách modelu a diskusi o nejvhodnějším modelu pro konkrétní účel použití.

Výzkum probíhal ve třech územích a byl realizován v období čtyř let díky podpoře GAČR projektu Metody umělé inteligence v GIS (Methods of artificial intelligence in GIS) (205/09/0793). Výzkum zahrnoval sběr dat vybraných lokalit ještě před použitím navržené metodiky. Tyto údaje byly prostřednictvím GIS připraveny v souladu s požadavky těchto metod.

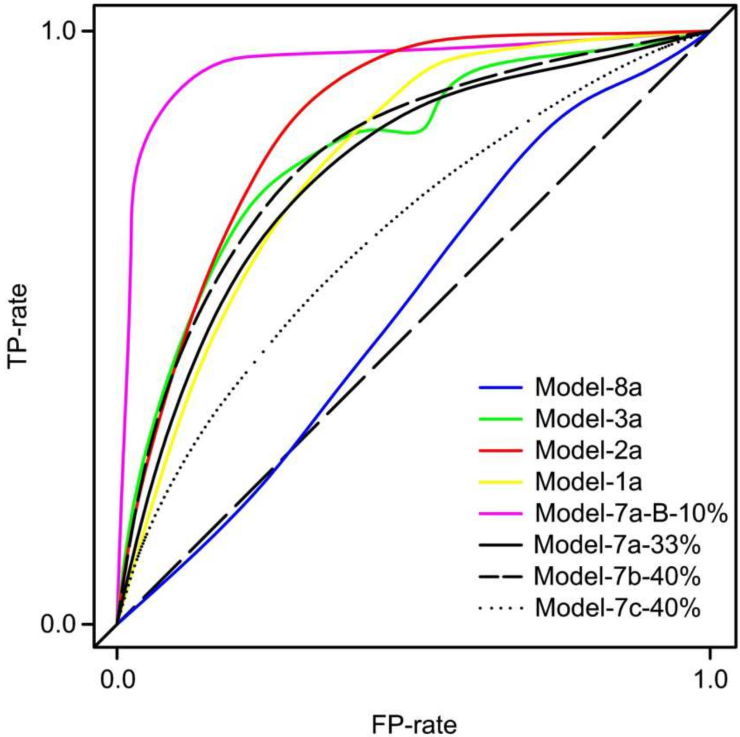
První zájmové území zahrnuje severozápadní svahy pohoří Fruška Gora (Srbsko) podél břehu Dunaje s rozlohou cca 100 km2, při čemž asi 10 % území je ovlivněno sesuvnými procesy. Většinou jde o projevy hlubokých rotačních a kompozičních sesuvů vyvinutých v neogenních pánvích. Vzhledem k velikosti území a podrobnosti dostupných vstupních dat byla pro analýzu zvolena 30metrové prostorové rozlišení a rastrový formát, což znamená, že za základní jednotku byl pixel o rozměru 30×30 m. Území bylo reprezentováno rastrovou vrstvou s 100 000 buňkami, které nesly informace o n-různých tematických vlastnostech území, takže každý pixel mohl být považován za vektor o n souřadnicích. Ve vstupních datech jsou zahrnuty především popis půdních sesuvů (získaný terénními metodami a metodami dálkového průzkumu Země, na kterém jsou odděleny pouze případy stejného typu, tj. hluboké sesuvy půdy typy earth slide podle přijaté klasifikace a pro které byly definované fáze aktivity) a jim odpovídající podmíněné faktory:

- sklon svahu, délka svahu, expozice, elevace, planární (horizontální) a profilové (vertikální) křivost svahu, TWI a vzdálenost od drenážní sítě (získané z digitálního modelu reliéfu, který byl modelován z topografické mapy v měřítku 1 : 25000 se základním intervalem vrstevnic 10 m),
- litologické jednotky, vzdálenost od zlomu a vzdálenost od významných geologických hranic (vyznačených na geologických mapách v měřítku 1 : 50000),
- vegetační pokryv (získaný z LANDSAT snímků s rozlišením 30 m a zpracovaný podle vegetačních indexů).

Použitím navržené metodologie pro daný soubor vstupních dat byly odvozeny různý modely náchylnosti a pokročilými metodami byly sestaveny i modely prostorové predikce sesuvů. Úspěšnost modelů je definovaná několika parametry, z kterých je nejdůležitějším ukazatelem ROC křivka, protože umožňuje kvalitativně-kvantitativní hodnocení modelu. Lze konstatovat, že použitím pokročilých metod (LR, DT a SVM) jsou jednoznačně nejvhodnější modely náchylnosti, které mají relativně vysokou přesnost, při které je negativní typ chyby (false negative) minimální. Nicméně některé modely, např. fuzzy model získaný vícevrstevnou fuzzy kombinací, vykazují určitý potenciál i přes mírně nižší přesnost a minimální nežádoucí chyby. Na druhé straně, prostorové predikce sesuvů u modelů založených na LR, DT a SVM technikám lze hodnotit jako úspěšné, oproti deterministickému modelu, který může být zcela ignorován a považován za nevhodný pro dané území. Pokročilé modely byly úspěšně použity i v případech s více než jednou kategorií sesuvy (aktivní a nečinné).

Druhé zájmové území se nachází v povodí řeky Stareč u Záhřebu (Chorvatsko), rozloha kolem 15 km2 s asi 10 % území ovlivněného sesuvnými procesy s tím, že mechanizmus a typologie sesuvů jsou zcela odlišné. Jsou zde mělké sesuvy v terciárních a kvartérních ložiscích, jejichž hlavní hnací sílou je eroze v kombinaci se srážkami. Použit byl soubor vstupních dat podle výše popsaného. Dále byla použita rastrová reprezentace o rozlišení 10 m (kvůli menší rozloze zájmového území a menším rozměrům sesuvů), takže celé území bylo vyjádřeno rastrovou vrstvou s 100 000 buňkami. Byla použitá podobná metodologie jako výše, ale v o něco menším objemu, protože některé podobné analýzy se základními metodami už na daném území proběhly. Proto byl důraz kladen na pokročilé metody, přesněji DT, resp. SVM techniky, a to pro jednu, resp. pět kategorií sesuvů (definovaných na základě jejich aktivit). Uvažovány byly také modely náchylnosti a predikce obou technik. Výsledky ukázaly o něco slabší úspěšnost v modelech náchylnosti a ještě menší v predikci samých sesuvy půdy. Zajímavé je, že lepší hodnocení vykázaly modely s několika kategoriemi sesuvů než jednodušší modely s jednou kategorií sesuvu. Tyto výsledky jsou pravděpodobně způsobeny nízkým prostorovým rozlišením rastru, ale i samou rozlohou zájmového území, přítomností velké řady stejných jevů (pět kategorií), které měly za následek tzv. overfit, tj. špatné naučenou relaci v procesu trénování algoritmu.

Poslední zájmové území je v okolí města Halenkovice ve Zlínském kraji (Česká republika) o rozloze přibližně 50 km2 s mělkými půdními sesuvy vyvinutými v terciárních flyších. V analýze byl použit soubor vstupních dat podobný ve výše popsaném textu, prostorové rozlišení gridu bylo 10 m, což vytvořilo rastrovou vrstvu o 500 000 buňkách. Důraz byl kladen na použití pokročilých metod, hlavně SVM techniky, a byl testován i i deterministický model s ohledem na to, že zde vyskytující se mělké sesuvy jsou teoreticky vhodné pro takový typ modelu. Modely založené na SVM technikách byly omezeny jen na predikční modely s tím rozdílem, že SVM model je omezený dodatečným optimalizačním postupem leave-one-out, zatímco deterministický model měl obě varianty (náchylnosti a predikce). SVM model lze ohodnotit jako průměrný, ale stále vykazující určitý potenciál v predikci. Deterministický model je v tomto případě nejednoznačný, protože některé části terénu modeluje velmi dobře, zatímco některé velmi špatně, a to i po komplexní optimalizaci, což omezuje model jen na určité geologické prostředí v zájmovém území.



Obr. 2. Srovnání výkonu ROC křivky

Některé z modelů jsou prezentovány prostřednictvím nástrojů internetového mapování a jsou k dispozici na adresách:

http://milosmarjanovic.pbworks.com/w/file/fetch/63738284/MyMapFruskaGora.htm,

http://milosmarjanovic.pbworks.com/w/file/fetch/63741247/MyMapStarca.htm,

http://milosmarjanovic.pbworks.com/w/file/fetch/63739326/MyMapHalenkovice.htm.

Závěrem lze konstatovat, že vytýčené cíle disertační práce byly splněny, a že navrhovaná metodologie podala dobré výsledky – v případech některých modelů méně úspěšné než v jiných. Modely náchylnosti (zejména modely získané použitím pokročilých metod) mohou najít uplatnění v různých aspektech plánování a projektování v regionálním měřítku, ale také pro regulaci ochrany, systémy včasného varování i pro pojišťovny. Zvláštní přínos mají predikční modely, na jejichž zdokonalování se stále může pracovat. Jejich aplikace se může navázat na uplatňování modelu náchylnosti, zatímco predikční modely mohly lze použit pro účely mapování sesuvů a tvorbu jejich databází v regionálním měřítku.

Curriculum Vitae

PERSONAL INFORMATION

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EDUCATION

2008–present	Department for Geoiformatics, Faculty of Science, Palacký University Olomouc - PhD studies
2002–2008	Department for Geotechnics, Faculty of Mining and Geology, University of Belgrade, Serbia –engineering degree

EXPERIENCE

2012–present	University of Belgrade (assistant-researcher), **project of Ministry of Education, Serbia:** Application of GNSS and LiDAR technology in monitoring of the terrain stability, TR 36009
2012–2013	Palacký University Olomouc (associate), **project of PU:** Maloformátové snímkování při studiu vlivu heterogenity povrchu na charakter stanoviště, PrF 2012 007
2010–2011	Palacký University Olomouc (associate), **project of PU:** Bezdrátový kontinuální monitoring, FRVŠ /2010
2009–2012	Palacký University Olomouc (researcher), **project of GACR:** Methods of artificial intelligence in GIS, 205/09/079

TEACHING

2012–present	exercising at Department of Geotechnics, BU, in: Principles of Engineering Geology, Engineering Geodynamics, Geo-static Calculus, Software in Geotechnics
2008–2011	teaching, exercising and examining at Department of Geoinformatics, PU, in: New Issues in Geosciences, Advanced Methods in RS, RS in Geology, GIS in Geology, Modeling in GIS

MOBILITY

2012	Faculty of Mining and Geology, University of Belgrade, Serbia, Department for Geotechnics (3 months)

2011	ESA Land Training Course, Krakow, Poland (2 weeks)
2011	IRPI Institute for Hydrogeological Hazards, Perugia, Italy (2 months)
2010	School of environment, The University of Auckland, New Zealand (1 month)
2010	LARAM advanced landslide assessment school, Salerno, Italy (2 weeks)

CONFERENCES

2013	Risk Identification and Land Use Planning for Disasters Mitigation 3rd Workshop, 6–9 March, Zagreb, Croatia
2013	GIS Ostrava 2013, 21-23 January, Ostrava, Czech Republic
2012	Urban Planning, Regional Development and Information Society (ICUPRDIS), 14–16 November, Venice, Italy
2012	1st InDOG Doctoral Conference, 29. October – 1. November, Olomouc, Czech Republic
2012	14th Symposium of Engineering Geology and Geotechnics (DGEITS), 27–28 September, Belgrade, Serbia
2011	2nd World Landslide Forum 2, 3–9 October, Rome, Italy
2011	International Workshop on DAtabases, TExts, Specifications and Objects (DATESO 2011), 20. April, Písek, Czech Republic
2010	Risk Identification and Land Use Planning for Disasters Mitigation 1st Workshop, 22–24 November, Dubrovnik, Croatia
2010	IAEG Congress 2010, 5–10 September, Auckland, New Zealand
2010	Land Use and Land Cover Changes in a Globalized World, 28. June – 1. July, Prague, Czech Republic
2010	GI Forum ’10, 6–9 July, Salzburg, Austria
2010	The State of Geomorphological Research, 11–13 May, Branná, Czech Republic
2009	International Conference on Intelligent Networking and Collaborative Systems (INCoS), 4-6 November, Barcelona, Spain
2009	Svahové deformace a pseudokarst 2009, 13–15 May, Vsetín, Czech Republic
2009	The State of Geomorphological Research, 15–17 April, Kašperské Hory, Czech Republic

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VZDĚLÁNÍ

2008–dosud	Katedra geoinformatiky,Přírodovědecká fakulta, Univerzita Palackého v Olomouci, doktorské studium
2002–2008	Katedra geotechniky, Hornicko-geologická fakulta, Bělehradská Univerzita, Srbsko, titul inženýra

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2012–dosud	Bělehradská Univerzita (výzkumný pracovník), **projekt Ministerstva školství, Srbsko:**AplikaceGNSSaLiDARtechnologie při monitorování stability terénu , TR 36009
2012–2013	Univerzita Palackého v Olomouci (spolupracovník), **projekt UP:**Maloformátové snímkovánípři studiu vlivu heterogenity povrchu na charakter stanoviště,PrF 2012 007
2010–2011	Univerzita Palackého v Olomouci (spolupracovník), **projekt UP:**Bezdrátový kontinuální monitoring, FRVŠ /2010
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PEDAGOGICKÁ ČINNOST

2012– dosud	Vyučující na Katedře geotechniky, BU: Základy inženýrské geologie, Inženýrská geodynamika, Geostatický výpočet, Software v geotechnice
2008–2011	Vyučující naKatedře geoinformatiky, PU: New Issues in Geosciences, Pokročilé metody v DPZ, DPZ v geologii, Geoinformatika v geologii, Modelování v GIS

STÁŽE

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2011	ESA Land Training Course, Krakow, Polsko (2 týdny)
2011	IRPI Ústav pro hydrogeologický nebezpečí, Perugia, Itálie (2 měsíce)
2010	Škola životního prostředí, Auckland University, Nový Zéland (1 měsíc)
2010	LARAM Školapokročiléhohodnocení sesuvů, Salerno, Itálie (2 týdny)

KONFERENCE

2013	Risk Identification and Land Use Planning for Disasters Mitigation 3rd Workshop, 6–9.3, Záhřeb, Chorvatsko
2013	GIS Ostrava 2013, 21-23.1, Ostrava, Česká Republika
2012	Urban Planning, Regional Development and Information Society (ICUPRDIS), 14–16.11, Benátky, Itálie
2012	1st InDOG Doctoral Conference, 29.10 – 1.11, Olomouc, Česká Republika
2012	14th Symposium of Engineering Geology and Geotechnics (DGEITS), 27–28.9, Bělehrad, Srbsko
2011	2nd World Landslide Forum 2,3–9.10, Řím, Itálie
2011	International Workshop on DAtabases, TExts, Specifications and Objects (DATESO 2011), 20.4, Písek, Česká Republika
2010	Risk Identification and Land Use Planning for Disasters Mitigation 1st Workshop, 22–24.11, Dubrovnik, Chorvatsko
2010	IAEG Congress 2010, 5–10.10, Auckland, Nový Zéland
2010	Land Use and Land Cover Changes in a Globalized World, 28.6 – 1.7, Praha, Česká Republika
2010	GI Forum '10, 6–9.7, Salzburg, Rakousko
2010	The State of Geomorphological Research, 11–13.5, Branná, Česká Republika
2009	International Conference on Intelligent Networking and Collaborative Systems (INCoS), 4-6.11, Barcelona, Španělsko
2009	Svahové deformace a pseudokarst 2009, 13–15.5, Vsetín, Česká Republika
2009	The State of Geomorphological Research, 15–17.4, Kašperské Hory, Česká Republika

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List of all author's publications / Úplný seznam publikací autora

Publications in J_{imp} category / Publikace v kategorii J_{imp}

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