GEOINFORMATION APPROACH FOR COMPLEX ANALYSIS OF MULTIPLE NATURAL HAZARD

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ABSTRACT:

Natural hazards are existence of natural components and processes, which create a situation that could negatively affect people, the economy and the environment. In this concern, they are associated with the probability of negative impacts and they are considered as limiting factors for people's lives and activities. Rising public awareness about natural hazards could improve the quality of life, save financial resources and even save lives. Methodological issues of complex analysis of multiple natural hazards in geographic information system (GIS) environment are presented in the current paper on the example of floods and landslide assessment. The complicated nature of natural hazards and the interrelations between natural components require a complex analysis of natural hazard factors and an integrated assessment taking into account all aspects of different hazards as well as the overall hazard resulting from a probable simultaneous occurrence of several adverse natural phenomena. A special attention is given to the data as one of the most important component of the analysis. Different data formats and particularities of spatial data interpretation in GIS environment are considered. Having regard the nature of the data and the phenomenon being evaluated, different GIS spatial analysis tools (fuzzy overlay, weighted sum, interpolation) are applied together with mathematical analyses. The results of the current research and suggested approach could support decision makers in territorial planning and risk management

1. INTRODUCTION

Natural hazards are considered as natural phenomena, which could have adverse impact on human life and activity. This determines the importance of these phenomena and the growing need to deepen the researches in this field, as well as taking into account their particularities in strategies and plans for territorial government. There are many publications considering single natural hazards and risks and still less of publications consider multiple hazards and risk. Multi-criteria index approach and GIS application in flood hazard is applied by many authors (Zheng et al., 2008; Kourgialas et al., 2011; Kazakis et al., 2015). Geomorphological properties of the area in regional scale are analysed by (Karagiozi et al., 2011) as a base for creating a flood hazard map. A probabilistic approach is proposed for assessment of landslide hazard by (Lari et al., 2014). The authors consider the particularities and relevance of the methodology for different methodologies of landslides. Multi-criteria evaluation and GIS application in landslide investigations are subject in several publications (Grozavu et al., 2010; Ilanloo. 2011; Costanzo et al., 2012; Pandey et al., 2014; Feizizadeh et al., 2014). In (Liu et al., 2016) hazards are determined as the presence of potentially damaging physical events in an area. According to (Di Mauro et al., 2006) the multi-hazard is considered in three dimensions: 1) different sources of hazard on one territory; 2) one hazardous event can trigger another hazardous event; and 3) two hazardous event without relation between them can appear simultaneously on one territory. Many papers analyze multiple hazards as a part of multi hazards risk assessment (Di Mauro et al., 2006; Kreibich, et al., 2014; Eshrati, 2015; Liu et al., 2016). Theoretical approaches and mathematical methods for modelling are applied in most of the researches (Rosso et al., 2006; Eshrati et al., 2015; Harab and Dell'Acqua, 2017). The review of the publications about multi hazard risk assessment and mapping shows that multiple hazard assessment and mapping is not only overlay of single hazard maps but also a special attention should be given on the interaction between hazard triggering factors.

The aim of the current research is to present some aspects of the capability of geoinformation approach in complex assessment of natural hazards on the example of floods and landslides events. The focus of the study is on the spatial analyzes in the GIS environment, application of fuzzy logic and the analysis of the factors influencing the natural hazards, as well as the complex impact of these factors. The paper does not aim to analyze the genesis of the hazardous events. The susceptibility of the territory to flood and landslide is evaluated, but the genetic link between them is not considered, whether the floods are the cause of landslide activation or the two phenomena occur independently of each other.

2. DATA AND METHODOLOGY

The first important part of the analysis of multiple natural hazard is identifying the hazards and analysing the factors triggering the hazardous events. In the current research, a complex analysis of natural hazards is done regarding floods and landslides. The following factors are analysed: rainfall, slope, rocks type, flow accumulation, distance from stream and land cover types. The data about natural hazards factors is entered, processed and analysed as different layers in ArcGIS (ESRI Inc.) environment. SRTM digital elevation model, DEM (Reuter, 2007; http://srtm.csi.cgiar.org) is used for generating slope map and analysing the spatial distribution of slopes, and for flow accumulation map. For this purpose, the raster image

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was projected in projected coordinate system (UTM) in order to transform angular geographic coordinates in Cartesian ones and to make calculations. The DEM is used also for elaborating a flow accumulation map, which represents a flow accumulation in each cell in the elevation raster and is an indicator for the areas water. Hydrology tools of ArcGIS Spatial Analyst is applied for this purpose. The precipitation data used in the research is taken from a climate model (https://en.climate-data.org). Monthly average amount and average annual amount of precipitation are used for calculating modified Fournier index (MFI) (Arnoldus, 1980) which indicates the rainfall intensity. The point data for the calculated index in 9 rain gauging stations is interpolated by inverse distance weighted method to present discontinues data in continues format. The lithology types are determined on the base of geological map, 1:100 000 (Kanchev, 1995). The rocks are grouped regarding their physical-mechanical and chemical properties, which influence the rocks permeability and in this relation determine the susceptibility of the territory to landslides and floods. The type of land cover influences on the time to drain the slope runoff (Nikolova and Zlateva, 2017) and in this regard, we analyze the land use/land cover (LULC) as flood and landslide factors. The LULC data is taken from CORINE Land Cover 2012 Project.

The complex analysis of multiple natural hazard is done by creating maps of the susceptibility of the investigated area to single hazardous event (floods and landslides), overlying these maps and taking into account the frequency of the occurrence of the event. The susceptibility maps are elaborated on the base of factor analysis and rating them according their importance for occurrence of hazardous event as follow: 1 – very low, 2 – low, 3 – moderate, 4 – high, 5 very high. Weighted sum overlay is used for a complex assessment. For determining of the weights we accepted that the layers of flood has 30% importance for the complex hazard level taking into account that floods could trigger landslides. The layer representing landslide susceptibility has 20% and to the layer of frequency of floods occurrence 50% are given. However, the equal level of hazard susceptibility, which could be observed in different parts of the investigated area the preventative activities and mitigation measures could be different in case of different duration of the occurrence of factors triggering the natural hazard.

In this relation and in case of shortage of data we applied fuzzy logic (Zimmerman, 1996) to make a complex assessment of multiple natural hazard level (Zlateva and Velev, 2013) and adding the time component (duration and total amount of rain). We designed fuzzy logic model with three inputs as follow: input 1 (with the highest importance for common hazard level) the total amount of intensive rain; input 2 (with moderate importance for common hazard level) – the multiple hazard level and input 3 (with less importance for common hazard level) the rain duration. In the proposed fuzzy logic model, the input linguistic variables, corresponding to the defined three inputs, are represented by three fuzzy membership functions: "Low (L)", "Moderate (M)", and "High (H)". The all input variables are assessed in the interval [0, 5] using triangular membership functions. The output of the fuzzy logic model (Complex assessment level of the multiple natural hazards) is described by five fuzzy membership functions: "Very low (VL)", "Low (L)", "Moderate (M)", "High (H)", and "Very high (VH)". The complex assessment level of the multiple natural hazards is assessed in the interval [0, 100] using triangular five membership functions.

3. STUDY AREA

The area subject of the current research is the upper part of the river Luda Kamchia catchment. It is situated in the Eastern Bulgaria (Figure 1). The relief is presented by mountainous river valleys, hilly to low-mountainous, the average altitude is around 750 m and the highest point is 1180 m. Besides the main drainage axis, the river Luda Kamchia, we can define 2 other relatively large rivers – Kotlenska and Neykovska. The low-mountainous relief and the geographical location of the area are a reason for moderate amount of precipitation, though intensive rain of 40 mm per 24 hours can be observed in 75 % probability (Climate reference book – Precipitation in Bulgaria, 1990). The most part of the investigated area is built of alternation of carbonate and non-carbonate rocks. The dense river network and variety of the topographic surface combined with the lithological substrate and the land use types influence the drainage of the surface water and the infiltration of the waters in the soils, and in this relation influence the occurrence of floods and landslides.

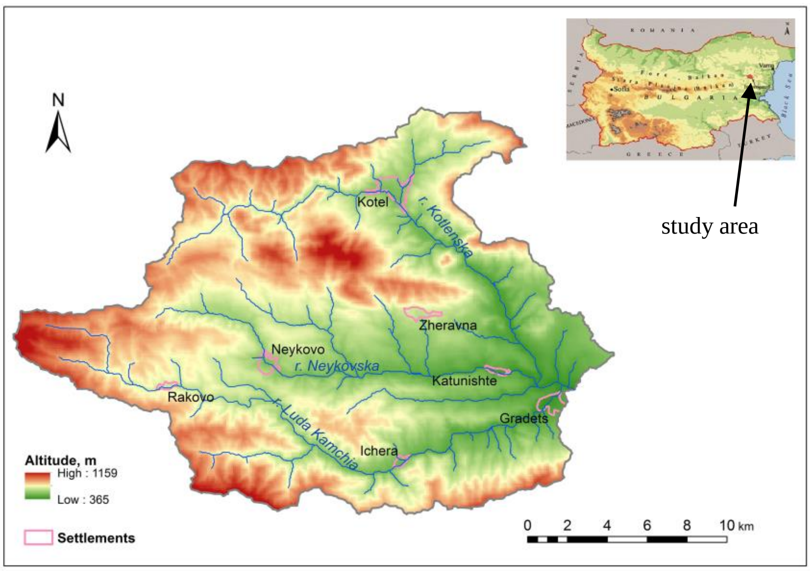

Figure 1. Study area

4. FACTOR ANALYSIS

Floods and landslides are natural hazards, which occurrence and character strongly depend on the environmental features and phenomena. In the current research, we considered rocks type, slope, rainfall, flow accumulation and distance from streams as natural hazards triggering factors. In the selection of factors, we were limited by the availability of the data and some factors like groundwater level and distance from faults were not considered. However we accept that in assessing natural hazards, simultaneous occurrence and the interaction of factors is of greater importance than the impact of the single factor. The first step in factor analysis is to analyze each one of the factors and to rate them according to their role for hazard occurrence (Table 1). The values of flow accumulation in the generated raster for the river Luda Kamchia basin are from 0 to 2 294 333. Taking into account the relief of the catchment and natural breaks classification method we reclassified the flow accumulation raster and set 1 for all cells with value less than 25 700 (very small importance for flood occurrences) and 5 for these with value great than 1 700 300 (very high importance for flood occurrence). The values between 25 700 and 1 700 300 are divided in 3 classes (with rates 2, 3 and 4) using natural breaks method (Nikolova and Zateva, 2017). Floods and landslides are considered as natural hazardous phenomena but human activity has also high impact on their behavior. In this regard, we considered LULC as a hazard triggering factor and rated the LULC types according to their impact on the floods and landslides occurrence.

The integrated impact of the above mentioned factors is evaluated and spatially presented by weighted overlay in ArcGIS environment. The weights of each one of the factors are determined using Analytic Hierarchy Process, AHP, (Saaty, 1987). The results are given in Table 2 and Table 3. The values in rows of the tables show the importance of the given factor to the factor in the column.

The analysis of the landslide and flood factors and the weights given in the tables show that rainfall and flow accumulation (presenting the water content of the area) are the most important factors for hazard occurrence. This group of factors normally have greater influence on floods than on landslides while the total weight of the influence of rocks type and slope is greater on landslides.

For example, unconsolidated non-carbonate rocks (gravel and sand) are usually susceptible to sliding on slope surface but the susceptibility increases if they are deposited on clay or other waterproof layer and it is greater at steeper slopes.

Factors	Susceptibility to flooding	Susceptibility to sliding
Rocks		
Unconsolidated non-carbonate rocks	4	5
Alternation of carbonate and non-carbonate rocks	4	4
Consolidated carbonate rocks	2	2
Consolidated non-carbonate rocks	5	2
Slope (degree)		
0 - 3	5	1
3 – 6	4	3
6 - 12	3	4
12 - 25	2	4
> 25	1	5
Rainfall intensity (MFI)		
56 – 58.9	2	2
59 - 63	3	3
Distance from streams (m)		
0 – 50	5	5
50 – 150	4	4
150 – 300	3	3
300 – 500	2	2
more than 500	1	2
LULC		
Urban areas	Not evaluated	Not evaluated
Industrial or commercial units	Not evaluated	Not evaluated
Mineral extraction sites	Not evaluated	Not evaluated
Non-irrigated arable land	3	2
Pastures	3	3
Complex cultivation patterns	3	3
Land principally occupied by agriculture with significant areas of natural vegetation	3	3
Broad-leaved forest	1	1
Coniferous forest	2	1
Mixed forest	1	1
Natural grassland	3	3
Transitional woodland/shrub	3	2
Sparsely vegetated areas	4	4

Table 1. Natural Hazard triggering factors and susceptibility rates

Factors	Rocks type	Slope	Rainfall	Flow accumulation	Distance from streams	Land cover	Total	Weights (%)
Rocks type	1.00	2.00	0.50	0.33	0.50	0.50	4.83	9.02
Slope	0.50	1.00	0.50	0.50	0.50	5.00	8.00	14.93
Rainfall	2.00	2.00	1.00	3.00	5.00	5.00	18.00	33.58
Flow accumulation	3.00	2.00	0.33	1.00	1.00	3.00	10.33	19.28
Distance from streams	2.00	2.00	0.20	1.00	1.00	2.00	8.20	15.30
Land cover	2.00	0.20	0.20	0.33	0.50	1.00	4.23	7.90
							53.60	100.00

Table 2. Landslides triggering factors and factor weights

Factors	Rocks type	Slope	Rainfall	Flow accumulation	Distance from streams	Land cover	Total	Weights (%)
Rocks type	1.00	3.00	0.20	0.25	0.25	2.00	6.70	10.23
Slope	0.33	1.00	0.25	0.25	0.50	2.00	4.33	6.61
Rainfall	5.00	4.00	1.00	4.00	3.00	4.00	21.00	32.05
Flow accumulation	4.00	4.00	0.25	1.00	5.00	5.00	19.25	29.38
Distance from streams	4.00	2.00	0.33	0.20	1.00	4.00	11.53	17.60
Land cover	0.50	0.50	0.25	0.20	0.25	1.00	2.70	4.12
							65.52	100.00

Table 3. Floods triggering factors and factor weights

On the other side the surface layer can start to slide even at small slopes (a bit steeper than 3^0) in case of intensive rain and high level of groundwater, and to be relatively stable at steeper slopes if there is no rain and the groundwater level is low. In this regard, when we talk about a complex phenomenon like natural hazard, interaction between the hazard triggering factors should be taken into account. Though the values of the importance of each one of the factors are determined by expert view applying the AHP minimizes the subjectivity of judgment when determining the weighting coefficients.

5. RESULTS

Taking into account the factors analysis the initial ArcGIS layers presenting each one of the considered factors are reclassified according to the determined rates to flooding and sliding (Table 1). Single hazard susceptibility maps (for floods and for landslides) are created by weighted overlay (Figures 2 and 3). The results show that the investigated part of the river Luda Kamchia catchment is very low to moderately susceptible to floods and landslides. There is a moderate probability of landslides occurring in larger areas of the investigated territory, while floods are probable in limited areas around the rivers. The created models are validated to the data of observed landslides (Geoprotection Ltd., Varna) and to flooded areas determined in Flood Risk Management Plan, FRMP, (Black Sea Directorate, Varna,). The results of validation show that the model of landslide susceptibility is more reliable. Floods susceptibility model is confirmed at the river Kotlenska and at the Gradets region, and future researches are needed to clarify the model in the other upper parts of the catchment. However, of some imperfection in the models we consider that they are enough reliable to direct attention of decision makers in planning preventative activities.

To evaluate the complex hazard we used weighted sum of layers of flood and landslide susceptibility, observed landslides and flooded areas (according to the above FRMP) with a repeat period of 20 years. The areas of observed landslides and flooded areas are rated with 4 (the scale 1 to 5 – very low to very high). Applying the weighted sum overlay and taking into account that floods can trigger landslides we accepted that the layers of modelled floods has 30% importance, modelled landslides layer is weighted by 20% and the layer of active landslides and flooded areas with a repeat period of 20 years is set to 50% of importance. The complex assessment is given on Figure 4. It shows slightly higher values in comparison of the single hazard layers.

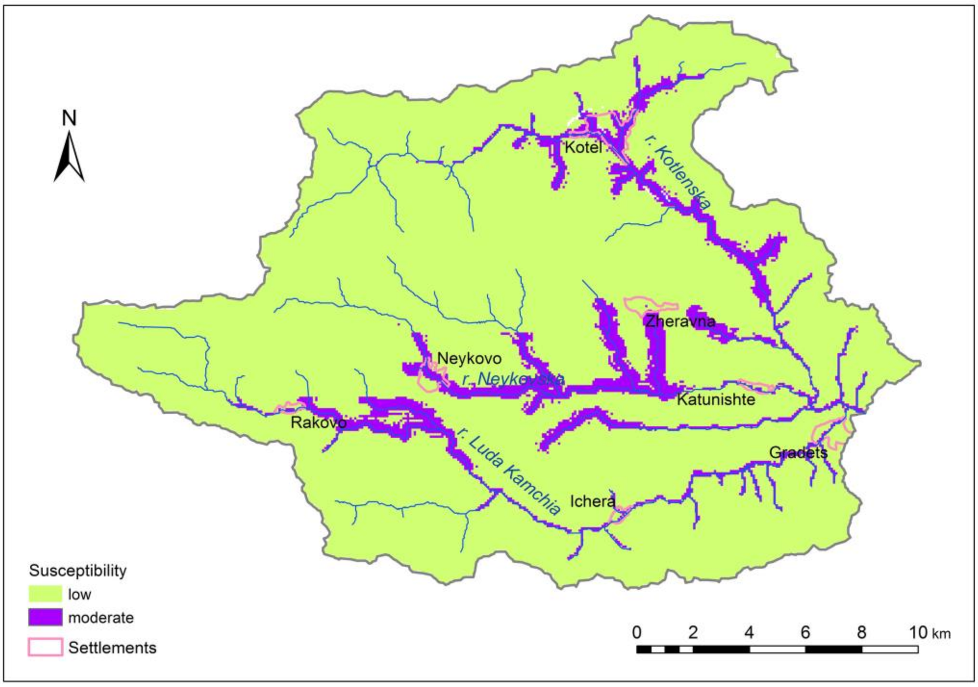

Figure 2. Flood susceptibility

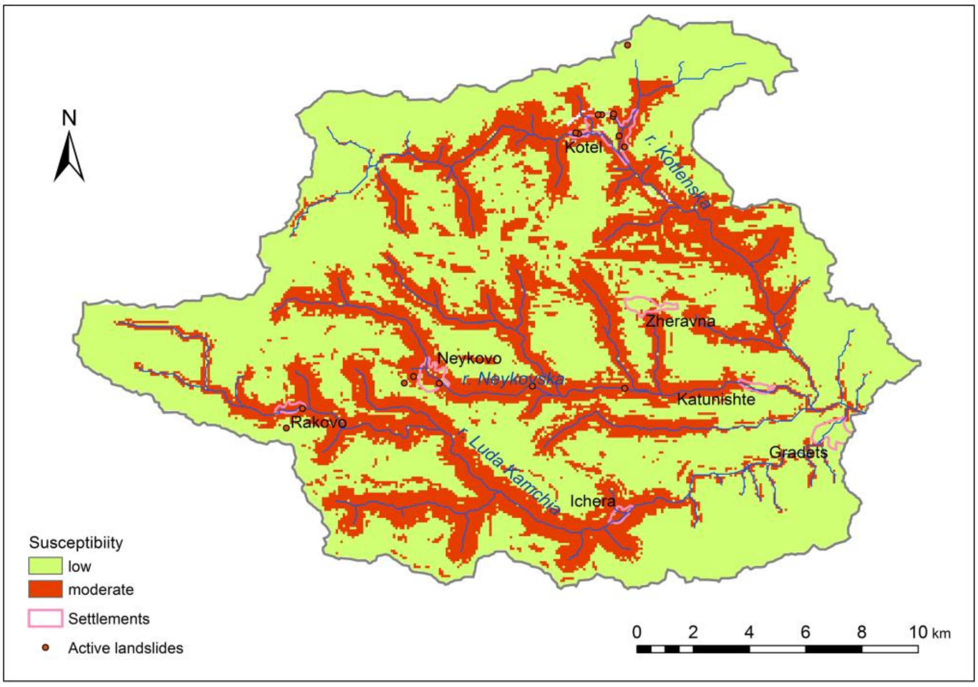

Figure 3. Landslide susceptibility

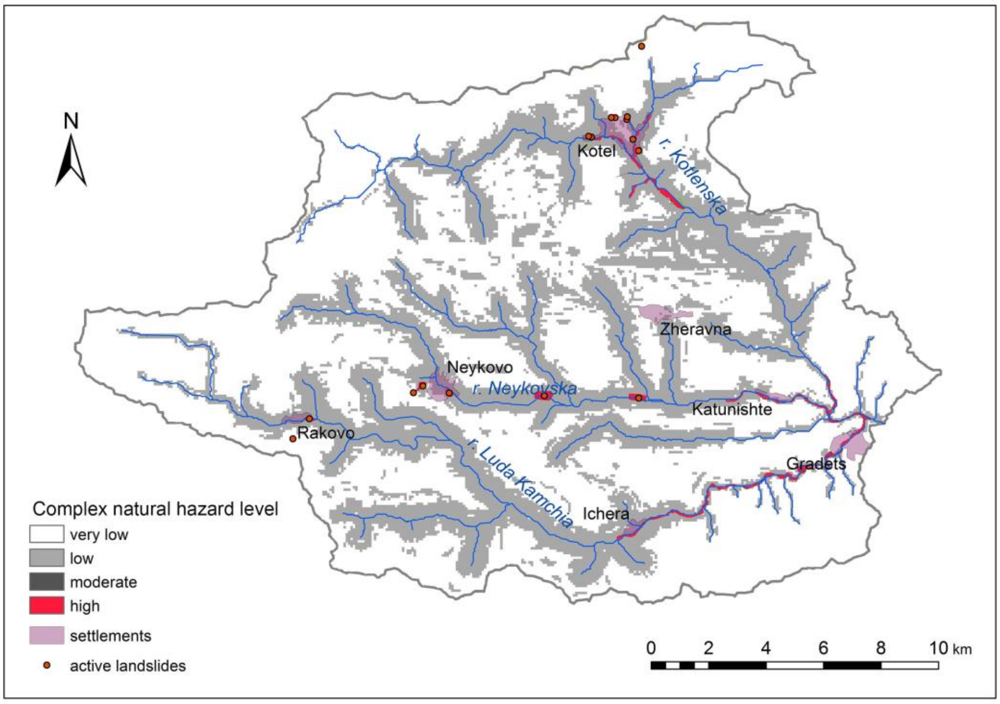

Figure 4. Multiple natural hazard

Taking into account the importance of rain as flood and landslide triggering factor we considered several scenarios adding the amounts of intensive rain and the period of rain to the fuzzy logic model for complex assessment of the multiple natural hazards (complex hazard level).

Here, the fuzzy logic model is designed in MATLAB computer environment using Fuzzy Logic Toolbox (Mathworks, 2014). The fuzzy logic model output is calculated as a weighted average of all the inference rules, which are defined in the fuzzy logic matrix.

The fuzzy logic model is based on Mamdani's inference machines (fuzzy logic matrix). The model is designed on based on max/min operations for fuzzy rules and center of gravity defuzzification.

The three inference surfaces of the fuzzy logic model for the two inputs and output are shown on Figures 5-7, respectively as follow (input1, input2, output1), (input1, input3, output1) and (input2, input3, output1).

We carried out several simulations by applying the fuzzy logic model to different input data. The obtained results are given in Table 4. Results show that we could have moderate hazard level at the tree inputs but the output could have high complex natural hazard level.

On the other side we could have 20 mm precipitation which are evaluated with low hazard level (input1), moderate hazard level (input2) and the output hazard level could be low if this amount of precipitation falls for 24 hours or moderate if it falls for 6 hours because the rain intensity is higher in the second case.

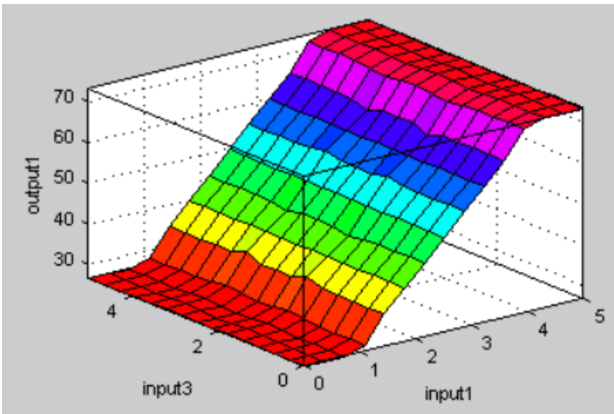

Figure 5. Inference surface for input1, input2, output1

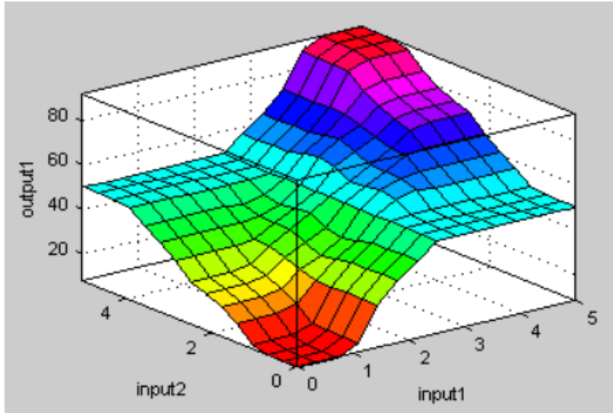

Figure 6. Inference surface for input1, input3, output1

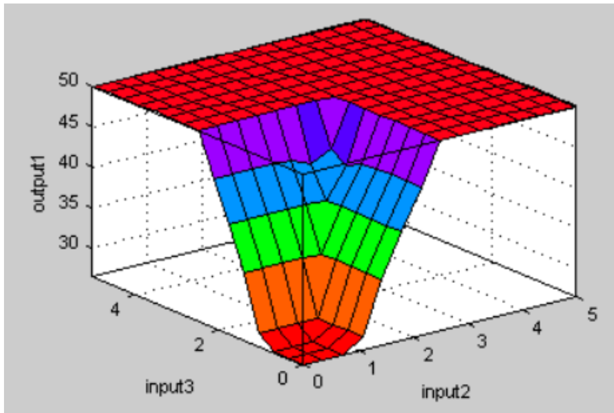

Figure 7. Inference surface for input2, input3, output1

Input 1	Input 2	Input 3	Output
Intensive rain, mm/ hazard level	Multiple hazard (landslides+floods) level	Rain duration, hours / hazard level	Common natural hazard level
40 mm / VH	M	48 h / L	H
25mm / M	M	24h / M	H
20 mm / L	M	24h / M	L
20 mm / L	M	6h / VH	M
20 mm / L	H	6h / VH	M
30 mm / H	L	6h / VH	H

Table 4. Complex level of multiple natural hazards based on the fuzzy logic model

6. CONCLUSIONS

The analysis of the multiple hazard is done on the example of floods and landslides susceptibility assessment and taking into account the data about active landslides and possible floods in the upper part of the river Luda Kamchia catchment. The lack of historical observations is considered as a limiting factor of the research.

The advantages of the presented methodology for complex analysis of multiple natural hazard by application spatial analyses in GIS environment is that it gives an information about the total hazard rate as well as for each one of the observed hazards. It also allows to see the factors triggering the particular hazardous event and this can be used by decision makers to take the relevant action in the particular situation.

The results of fuzzy logic approach strongly depend on the way of setting the hazard factors in the different inputs, the chosen membership functions and defined inference rules. In this relation future researches are to be directed to the expanding the scope of hazard triggering factors and investigating the interactions between them as well as to finding the best way for heightening the single hazards in the complex multiple hazards.

The GIS database built as a result of the research can be easily updated and allows adding new factors of hazard which enable expanding the analyses. The suggested models of hazard susceptibility and common hazard level can be used as a first stage of multiple risk assessment and are tools to support decision makers and planning experts in the process of mitigating the impact of hazardous event and better territorial development.

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REFERENCES

Arnoldus, H.M.L., 1980. An approximation of rainfall factor in the universal soil loss equation. *Assessment of erosion* (Boodt and Gabriels, eds.), Wiley, Chichester, U.K., pp. 127-132.

Climate data for cities worldwide https://en.climate-data.org

CORINE Land Cover 2012 project, 2012. http://eea.government.bg/bg/projects/korine-14/index

Costanzo, D.; Rotigliano, E.; Irigaray, C.; Jim´enez-Peralvarez J. D.; Chacon, J., 2012., Factors selection in landslide susceptibility modelling on large scale following the GIS matrix method: application to the river Beiro basin (Spain). *Nat. Hazards Earth Syst. Sci*., 12, pp. 327–340.

Di Mauro, C.; Bouchon, S.; Carpignano, A.; Golia, E and Peressin, S., 2006. Definition of multi-risk maps at regional level as management tool: Experience gained by civil protection authorities of Piemonte region. *In Proc. of the 5th Conf. on Risk Assessment and Management in the Civil and Industrial Settlements*, http://conference.ing.unipi.it/vgr2006/archivio/.

Eshrati, L.; Mahmoudzadeh, M.; Taghvaei, M.; 2015. Multi hazards risk assessment, a new methodology. *Int. Journal of Health System and Disaster Management,* 3 (2), pp. 79-88.

Feizizadeh, B.; Roodposhti, M. S.; Jankowski P.; Blaschke, T., 2014. A GIS-based extended fuzzy multi-criteria evaluation for landslide susceptibility mapping. *Computers & Geosciences,* 73, pp. 208–221.

Flood Risk Management Plan, Black Sea Directorate – Varna, https://www.bsbd.org/uk/FR_mplans.html

Geoprotection Ltd. – Varna, http://varna.geozashtita.bg/

Grozavu, A.; Margarint, M. C.; Patriche, C. V., 2010. GIS applications for landslide susceptibility assessment: a case study in Iași County (Moldavian Plateau, Romania). *Transactions on Information and Communication Technologies*, 43, pp. 393-404

Harab, M. M. and Dell'Acqua, F., 2017. Remote Sensing in Multi-Risk Assessment: Improving disaster preparedness. *IEEE Geoscience and Remote Sensing Magazine,* 5(1), pp. 53-65.

Ilanloo, M., 2011. A comparative study of fuzzy logic approach for landslide susceptibility mapping using GIS: *An experience of Karaj dam basin in Iran*. *Procedia Social and Behavioral Sciences,* 19, pp. 668–676.

Kanchev, I., 1995. *Geological map of Bulgaria*, map sheet Sliven. Scale 1:100000. Geology and Geophysics JSC, Sofia.

Karagiozi, E.; Fountoulis, I.; Konstantinidis, A.; Andreadakis, E.; Ntouros, K., 2011. Flood hazard assessment based on geomorphological analysis with GIS tools – the case of Laconia (Peloponnesus, Greece). *GIS Ostrava 2011, Eight International Symposium, Proceedings*, pp. 201 – 216

Kazakis, N.; Kougias, I.; Patsialis, T., 2015. Assessment of flood hazard areas at a regional scale using an index-based approach and Analytical Hierarchy Process: Application in Rhodope–Evros region, Greece, *Science of the Total Environment,* 538, pp. 555–563

Kourgialas, N. N.; George P. Karatzas, G. P., 2011. Flood management and a GIS modelling method to assess flood-hazard areas—a case study. *Hydrological Sciences Journal*, 56(2), pp. 212-225, doi: 10.1080/02626667.2011.555836

Kreibich, H.; Bubeck, P.; Kunz, M.; Mahlke, H.; Parolai, S.; Khazai, B.; Daniell, J.; Lakes, T.; Schroter, K., 2014. A review of multiple natural hazards and risks in Germany. *Nat Hazards,* 74, pp. 2279–2304.

Lari, S.; Frattini, P.; Crosta G. B. 2014. A probabilistic approach for landslide hazard analysis. *Engineering Geology*, 182, pp. 3-14.

Liu, B.; Siu, Y. L.; Mitchell, G.; Xu, W., 2016. The danger of mapping risk from multiple natural hazards. *Nat Hazard,* 82, pp. 139–153, doi 10.1007/s11069-016-2184-5

Mathworks, 2014. *MATLAB*, https://www.mathworks.com/

Nikolova V. and Zlateva P., 2017. Assessment of Flood Vulnerability Using Fuzzy Logic and Geographical Information Systems. In: Murayama Y., Velev D., Zlateva P., Gonzalez J. (eds) *Information Technology in Disaster Risk Reduction*. *ITDRR 2016. IFIP Advances in Information and Communication Technology,* 501. Springer Cham; pp. 254-265.

Pandey, A. R.; Shahbodaghlou, F., 2014. Landslide Hazard Mapping of Nagadhunga-Naubise Section of the Tribhuvan Highway in Nepal with GIS Application. *Journal of Geographic Information System*, 6, pp. 723-732

Rosso, R.; Rulli, M. C.; Vannucchi, G. 2006. A physically based model for the hydrologic control on shallow landsliding. *Water Resource Research*, 42, W 06410, doi:10.1029/2005WR004369

Reuter H.I.; Nelson, A.; Jarvis, A., 2007. An evaluation of void filling interpolation methods for SRTM data. *Int. Journal of Geographic Information Science,* 21(9), pp.983-1008.

Saaty, R., 1987. The analytic hierarchy process – what it is and how it is used. *Mathematical Modelling,* 9(3-5), pp. 161-176

Zheng, N.; Tachikawa, Y.; Takara, K., 2008. A Distributed flood inundation model integrating with rainfall-runoff processes using GIS and remote sensing data. *The Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences.* XXXVII (B4), Beijing, pp. 1513-1518.

Zimmerman, H., 1996. *Fuzzy set theory and it applications*. Kluwer Academic Publishers, Norwell MA, USA.

Zlateva, P. and Velev, V., 2013. Complex risk analysis of natural hazards through fuzzy logic. *Journal of Advanced Management Science*, 1 (4), pp. 395-400.