INTEGRATED APPROACH IN GEOTECHNICAL RISK ANALYSES FOR BRZA VODA WATERSHED IN POLOG REGION

UDC: 528.067(497.75:282)
DOI: https://doi.org/10.37658/MGD24039j

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ABSTRACT

The article presents one approach used in geotechnical risk analyses for Brza voda (Poroj) river watershed, located in Macedonian Polog region. This is an area with frequent occurrences of erosion, flood and landslides events, where in certain zones of the catchment area, there are a high level of risks on exposed populated areas, traffic and energetic infrastructure and the natural environment. The methodology integrates several steps in risk analyses. As a support to the geotechnical analyses, detecting of unstable zones applying Differential Interferometry Synthetic Radar Aperture technics, Light Detection and Ranging surveys, conventional methods for landslide detection, analyses of erosion potential, hydrological and cost-benefit analyses are used. Risk assessment is based on probabilistic stability analyses for a landslide in the area of Gjermo village and shallow landslide analyses for the entire investigated area. Possible consequences form extreme hydrological and sliding events on the existing infrastructure, small hydropower plants and population are also analyzed in order to form a pair of values in risk matrix as a combination of probability of failure and economic impacts. In addition, several scenarios of susceptibility maps from shallow sliding assessments are presented. The final product is a simple risk map which is one of the elements and background for detailed design of protection measures in the catchment area.

Keywords: Erosion, economic impact, geotechnical risk, landslide, probability of failure, risk matrix

INTRODUCTION

Poroj River watershed is a part of Macedonian Polog region and it is situated in NW part of the country. This area has complex morphological elements related to complicated tectonic and geological settings (Figure 1).

The behavior of the natural system also depends on hydrological aspects. The study area is characterized by the annual average rainfall with values ranging from 600 to more than 1250 mm/year. The origin of the river is connected with an altitude of 2315 m, while the highest peak of the watershed is about 2375 m. The position of Gjermo village is in a mid of the basin at an elevation of about 1070 m, while the toe of the catchment area is related to village of Poroj at the transition from mountain to plain area, with elevations between 500 to 600 m (Figure 2).

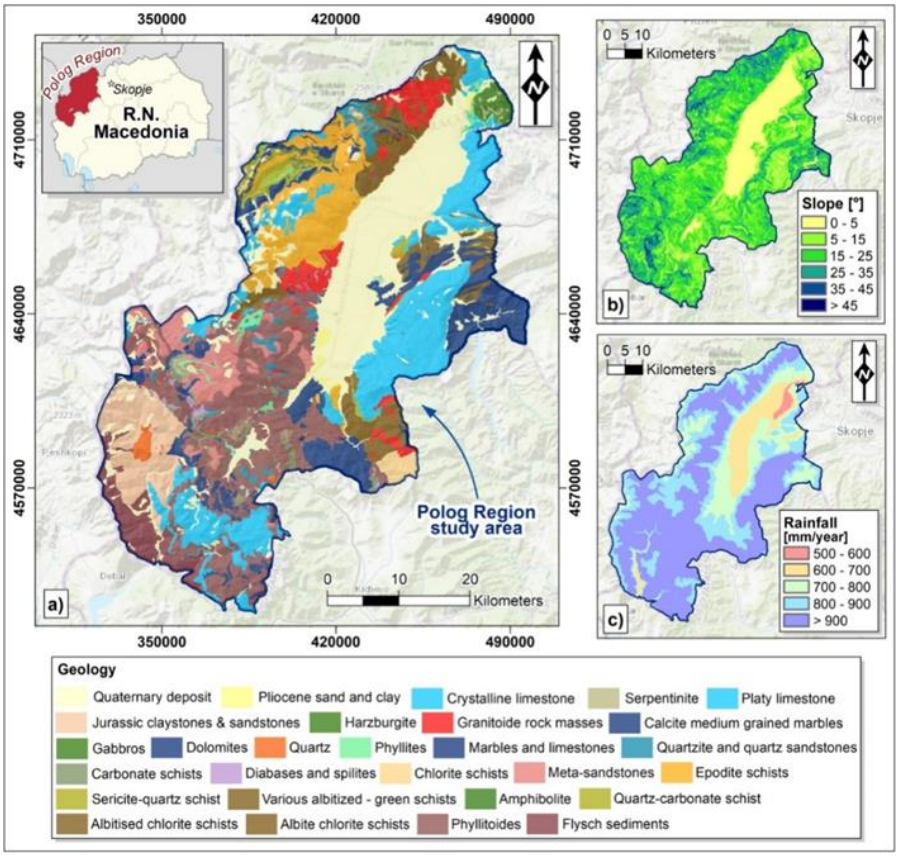


Figure 1. Presentation of study area: a) geological map, b) slope map and c) rainfall map.
Source: Jovanovski et al., 2021a.

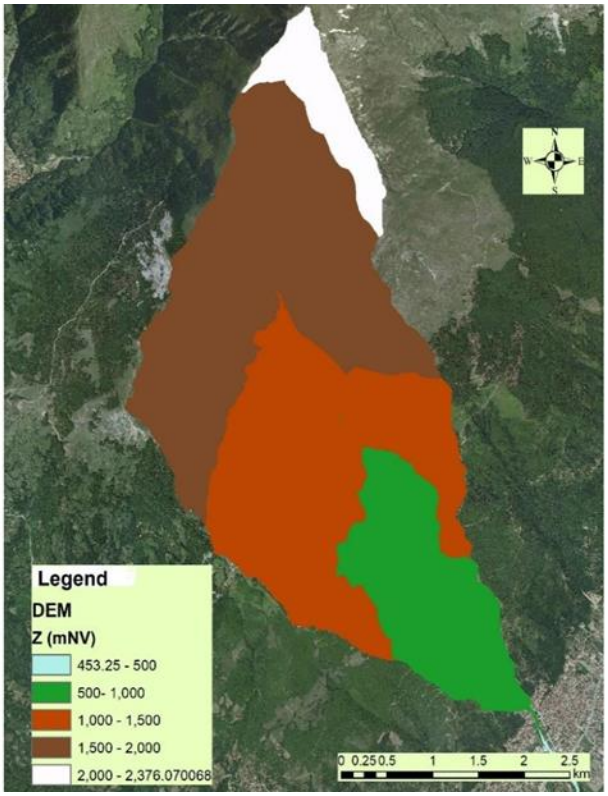


Figure 2. Digital Elevation Model of the Poroj River watershed.
Source: Jovanovski et al., 2021a.

One of the main risks on the population and infrastructure is a deep landslide located in the zone of village Gjermo. Based on historical data, the initial appearance of the landslide dates back to 1962, while several larger reactivations are observed after periods of intense rainfalls, such as in 1979, 1982 and 2006. On the other side, the densely populated village Poroj is also often affected by flooding from the Brza voda (Poroj) River. It is clear that the complicated natural and man-made factors, create preconditions for high level of risks to population and infrastructure in this watershed. Therefore, development of consistent risk management strategy is necessary. In this case, the activities are connected with preparation of multidisciplinary project funded by the United Nations Development Program (UNDP). The details can be found in Jovanovski et al. (2021a, 2021b). Main idea in the methodology is to find optimal relation between investments in protection and acceptable level of risks. The presented methodology in some elements is similar with known world practices according to Andersson et al. (2014) or Van Westen et al. (1996). Some adaptations and developments are presented based on the specifics of analyzed region.

DATA AND METHODS

The basics of applied methodology are related to step-by-step procedure and hierarchical process of analyses. Analyses of data from previous phases of investigations, erosion potential, rainfall and risk analyses, in correlation with complex socio-economic analyses for the Polog area, are very important. Simple flow-chart that explains the main steps in the methodology is presented in Figure 3.

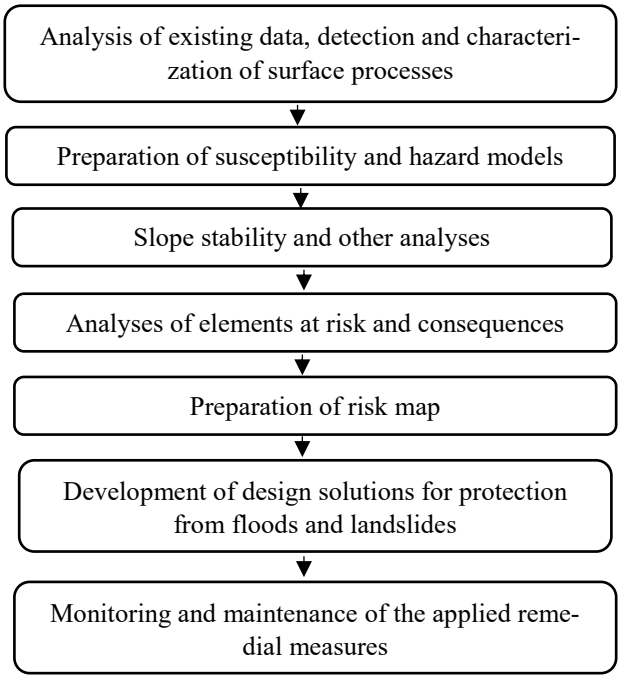


Figure 3. Flow-chart for suggested methodology of risk analyses

The leading idea in the procedure is to include consequences on the nature, infrastructure and population expressed in financial manner, supported with technical analyses. In this case,

several grades of landslide probability and grades of consequences assessed by monetary valuation are combined as pairs of values in a so-called risk matrix.

A process of detection of unstable zones starts with review of existing data from the landslide inventory, morphological, geological, tectonic, climatic, and other characteristics of the terrain. This is the basis for further analyses in regards to assessment of possible development of landslides, zonation of the area into homogeneous domains and ranking them according to the degree of landslide susceptibility, hazard or risk. The detection of landslides is done using DInSAR (Differential Interferometry Synthetic Radar Aperture) technology and LiDAR (Light Detection and Ranging) scanning, as the most advanced techniques in this field of engineering. The data on landslides obtained by these methods, together with archive data on landslides, form the landslide inventory. Details can be found in Peshevski (2015) or in Nedelkovska (2023).

The next step is to prepare landslide susceptibility and erosion potential models using the principles in analyses from "wider to narrower" areas. Some examples of prepared maps with defined erosion coefficient for the region or landslide susceptibility are presented in Figure 4.

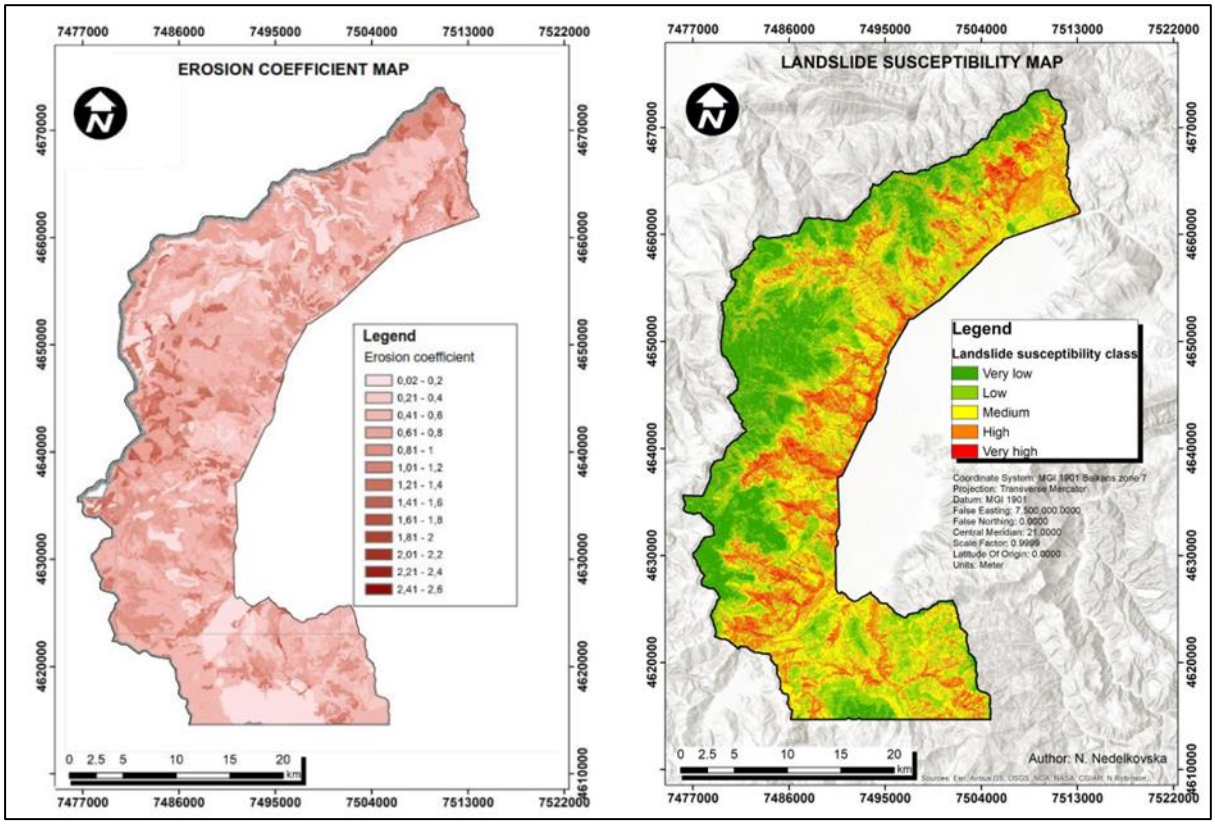


Figure 4. Presentation of maps with a defined erosion coefficient (left) and the landslide susceptibility map of the Polog area (right). Source: (Nedelkovska, 2023)

Detailed models are mainly prepared using geotechnical analyses. For whole Brza voda watershed, shallow landslide susceptibility is defined using the "infinite slope method" stability analysis, by calculating safety factor (F) of an area with the equation 1:

$$F = \frac{C_s + C_r}{\gamma_e D \sin\theta} + (1 - m\frac{\gamma_w}{\gamma_e})\frac{\tan\varphi}{\tan\theta} \qquad (1)$$

wherein and C_r are effective soil and root cohesion (kN/m^2), D is soil depth above the failure plain (m), φ is angle of internal friction of the soil (º), θ is slope angle (º), γ_w is unit weight of water (kN/m^3), γ_e is effective unit weight of the soil (kN/m^3), and m is wetness index.

The parameter wetness index (m) is expressing the relative position of the water table H/D, where H is the saturated thickness of the soil above the failure plane, and D is the total depth of the soil above the failure plane. The method is explained by Skempton and Delory (1957). The range of values for the basic physical-mechanical geotechnical properties of lithological units in Polog region are presented in Table 1.

Table 1. Values of the basic geotechnical parameters for the lithological units

Lithological unit	Dry unit weight γ_d [kN/m^3]		Saturated unit weight γ_s [kN/m^3]		Cohesion C_s (kPa)		Angle of internal friction φ (º)	
	min	max	min	max	min	max	min	Max
Alluvial sediments	17.0	18.6	20.0	21.6	0.0	16.0	20.0	36.0
Proluvial sediments	15.5	16.5	18.5	19.5	1.0	22.0	24.0	32.0
Diluvial/eluvial sediments	16.0	18.5	19.0	21.5	10.0	30.0	25.0	29.0
Fluvio/glacial sediments	14.0	16.0	17.0	19.0	8.0	20.0	22.0	32.0

Next stage in geotechnical analyses was to define calculation model for deep sliding at Gjermo landslide. While preparing the model, some known data for the geological characteristics of the landslide was used. It should be noted that the results must be considered with precaution, because there are no enough data from detailed geotechnical investigations for the whole landslide zone. Having in mind several reactivations of the sliding processes, only residual values are relevant along the sliding surface. In this case, some minor values of the cohesion, for calculation reason, are used in the analyses. One of the applied calculation models for so-called planar failure mechanism is presented in Figure 5, while main input parameters are given in Table 2.

Table 2. Input geotechnical parameters for calculation model of Gjermo landslide.

Material	γ [kN/m^3]	C [kPa]	φ [°]
Red color (landslide body)	19.0	2.0	20.5
Yellow color (soil debris)	20.0	10.0	25.0
Green color (shist rock mass complex)	26.0	80.0	34.0

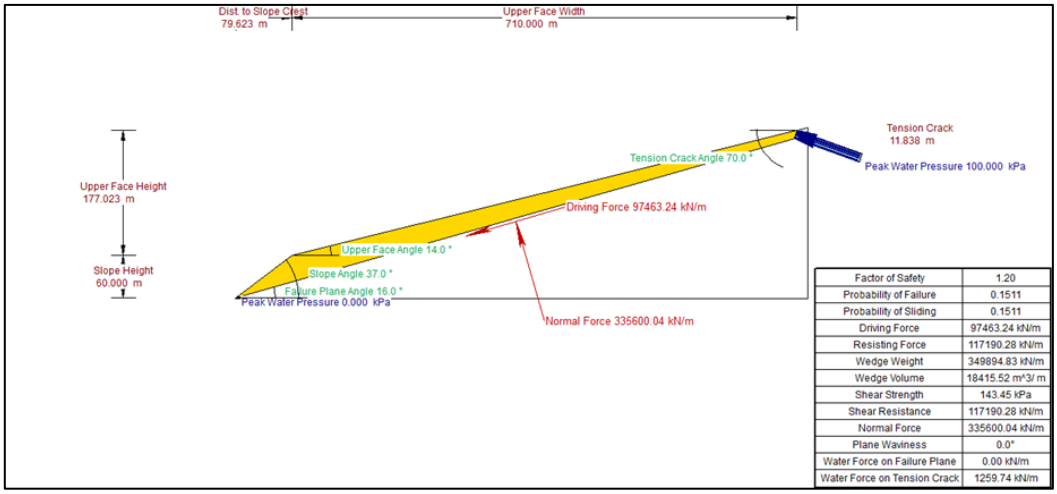
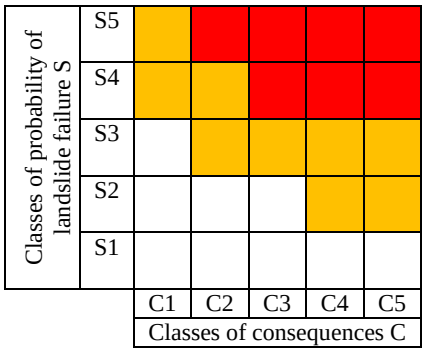


Figure 5. Calculation model for stability analyses for Gjermo landslide

Very important step in the risk assessment is the determination of the expected damages and losses from possible fast re-activation of Gjermo landslide. Exposed elements at risk from the landslide and the adopted risk matrix are presented in Figure 6.



Elements at risk of landslide	Unit
No. of affected houses	170
Total houses area (m^2)	15.274
No. of houses in low landslide risk	64
No. of houses in medium landslide risk	2
No. of houses in high landslide risk	104
Affected critical infrastructure	2
Length of affected road infrastructure (m)	1.400
Directly affected population	1.020
Total affected population	3.862
Small Hydro Power Plants	3

Figure 6. Risk matrix used for preparation of risk map combining the classes of consequences (C) expressed as socio-economic costs and classes of probability of landslide failure (S); red color is for areas with high landslide risk; orange color is for areas with medium landslide risk; white color for areas with low landslide risk.

The adopted risk matrix is composed as a combination of 5*5 consequences (C) and probability of failure classes (S). Consequences are analyzed from aspect of numbers of total affected population, possible damages on houses, possible number of people killed, damages on road infrastructure, several small Hydro Power Plants (HPP), environmental consequences, requirement of remediation, remedial costs etc. Land sliding probability is assessed using variation of input parameters in some range, by calculations for the geotechnical model presented in Figure 5. The probabilistic approach in definition of Safety Factor and Probability of Failure is used. Main results are presented further in the text.

RESULTS

Numerous scenarios are developed in the process of geotechnical analyses. For example, in definition of shallow landslide susceptibility and stability, the following scenarios were analyzed:

- Scenario 1: minimum values of geotechnical parameters and m=0.35
- Scenario 2: minimum values of geotechnical parameters and m=0.7
- Scenario 3: minimum values of geotechnical parameters and m=1
- Scenario 4: average values of geotechnical parameters and m=0.35
- Scenario 5: average values of geotechnical parameters and m=0.7
- Scenario 6: average values of geotechnical parameters and m=1

In Figure 7, results for only one scenario are presented, in order to illustrate the distribution of shallow land sliding susceptibility zones at the whole Brza voda river catchment area. The prepared susceptibility maps indicate that the shallow landslides model depends a lot on the degree of saturation. It is notable that in any scenario, the area of Germo village landslide is in the zones where factor of safety is below acceptable value, i.e. F<1.

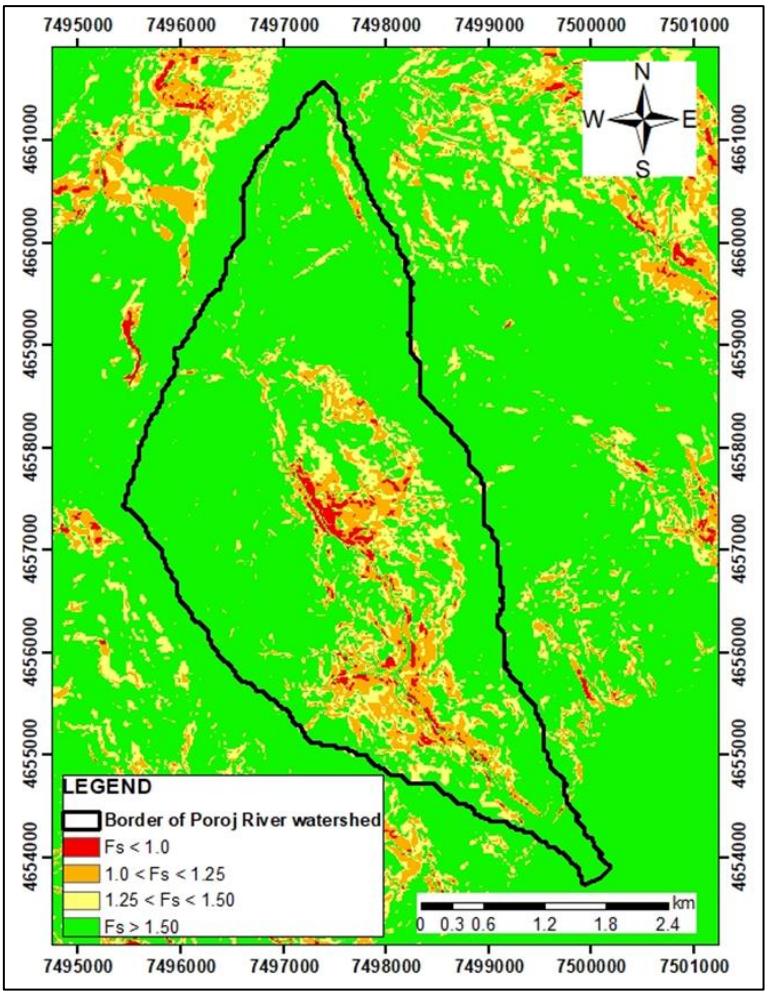


Figure 7. An example for model of shallow landslide susceptibility of Brza voda river watershed - Scenario 5-average values of geotechnical parameters and m=0.70. Red arrow indicates the area of Gjermo landslide.

Main results for the calculation model presented in Figure 5 are listed in Table 3. Several combinations for saturation of the tension crack of the landslide and some values for seismic coefficient are considered in the analyzed scenarios.

Table 3. Results from stability analyses along sliding zone of Gjermo village using ROCPLANE program

Case 1. Water in tension crack only, without seismic action	Case 2. Water along failure plane, without seismic action	Case 3. Water at tension crack, seismic coefficient 0.05	Case 4. Water at tension crack, seismic coefficient 0.08
Probabilistic Analysis Probability of Failure (PF): 0.1511 Normal Reliability Index: 1.17756 Lognormal Reliability Index: 1.20794 Factor of Safety: 1.20241	Probability of Failure (PF): 0.2709 Normal Reliability Index: 0.673166 Lognormal Reliability Index: 0.647796 Factor of Safety: 1.13397	Probabilistic Analysis Probability of Failure (PF): 0.6094 Normal Reliability Index: -0.409047 Lognormal Reliability Index: -0.453805 Factor of Safety: 1.01093	Probability of Failure (PF): 0.892 Normal Reliability Index: -1.27532 Lognormal Reliability Index: -1.25256 Factor of Safety: 0.930095

From the presented results it is obvious that factor of safety is in range of values Fs=0.93 – 1.2, depending on the chosen input variables in the calculation model. It is evident that even

small values of pore water pressures and/or minor seismic influences, lead to unstable conditions, with probability of failure PF=15-89%. Such values are usually not allowed for typical engineering cases. In practice, a minimum recommended value for Factor of safety in dry conditions is F>1.5, while for seismic actions F>1.1. In this case, it is obvious that such values are hard to be fulfilled. The results indicate that the landslide zone is close to the limit equilibrium. DinSAR analyses for the period 2015-2021 give values for velocities of landslide movements typical for slow-moving landslides. Results are presented in Table 4.

Table 4. DInSAR data for landslide velocity movement for Gjermo village: Source: Jovanovski et al. (2021)

Landslide	DInSAR average velocity [mm/year]			
	|min|	|max|	|avg.|	std. dev.
Gjermo village	4.70	38.0	9.10	13.63

As a final product from all analyses, a simple risk map is prepared (Figure 8).

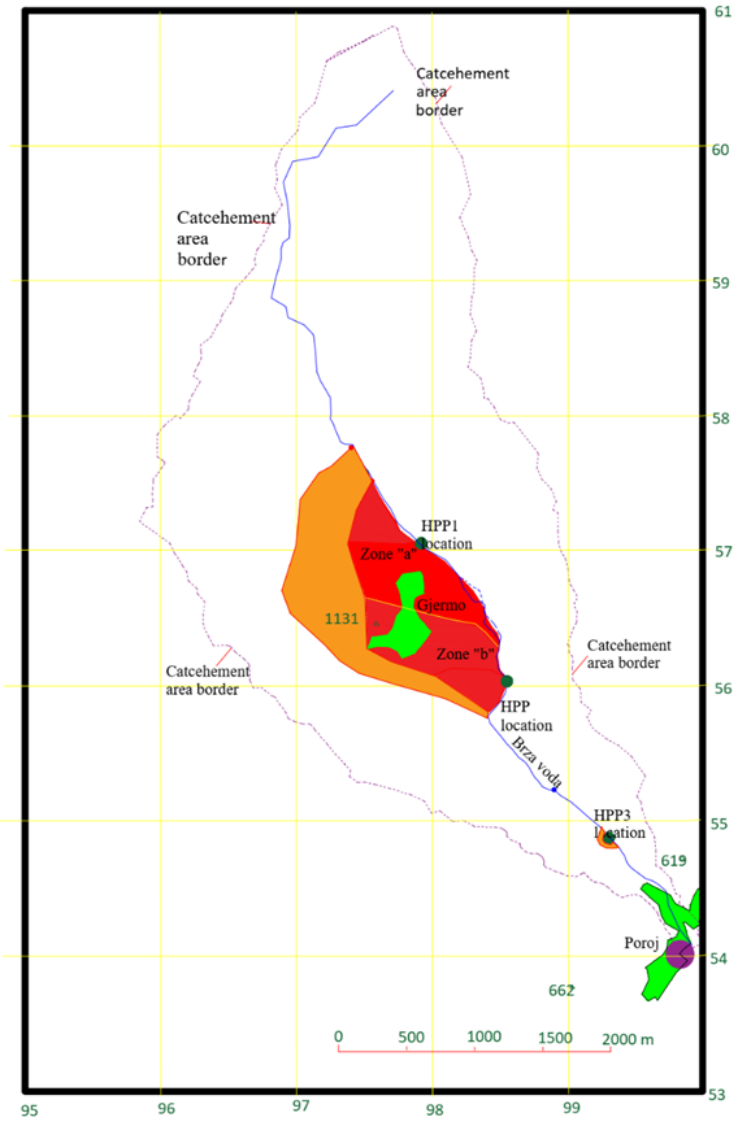


Figure 8. Risk map for Poroj River (Brza voda) catchment area (red color is for areas with high landslide risk; orange color is for areas with medium landslide risk; white color for areas with low landslide risk; green color indicates location of settlement).

DISCUSSION

The presented risk map in Figure 8 indicates that three main zones are defined from aspect of possible risk. The red colored zones are with highest risks, because they are related to the populated areas, presence of local roads and hydropower plants etc. The orange-colored zones are with medium risks, where mainly some local infrastructure is affected while the population is not directly affected. The white zones are with low risk, because only some agricultural areas can be affected by the zone of sliding.

Leading principles in risk zonation are based on the findings presented in Table 5. There, for each class, the values of probability of failure defined with stability geotechnical analyses and expected socio-economic costs representative for the case of Poroj River catchment area are presented. The zones of highest risks are marked with red color. In the analyses, some value for Hydro Power Plants (in total about 5-6 million Euros) is added to the previous prepared Cost-Benefit Analyses (CBA). The details of CBA analyses overcome the frame of this article, and they can be found in UNDP study from 2021 (Jovanovski et al. 2021).

Table 5. Landslide probability and consequence class intervals

Probability / consequence class	1	2	3	4	5
Probability of failure	<3.0E-4	3.0E-6 – 1.0E-4	1.0E-4 – 3.0E-3	3.0E-3 – 1.0E-1	>1.0E-1 1
Socio-economic cost adopted to MKD conditions in million Euros	<0.0738	0.0738-0.4305	0.4305-1.845	1.845-7.995	>8

With idea to ensure analytical connection for each value of probability of failure and socio-economic cost, in Figure 9 is presented the established correlation between the number of the consequence classes (from 1 to 5) with the value of probability of failure and of the cost.

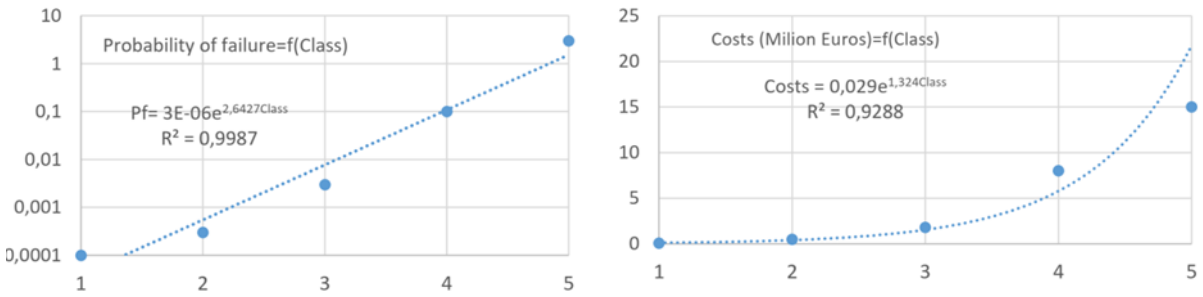


Figure 9. Diagrams for continuous definition of probability of failure (left) and costs (right) for fast prognosis of level of risks.

The presented diagrams can help in definition of risk level for each point of some analyzed area, using adequate ratings for classes. This idea is in a process of development, in a similar manner like the known polynomial interpolation method (PIM) used for solving many problems in geotechnics (Nedelkovska et al. 2017). Such methodology suggests need of integral use of data from landslide inventory, susceptibility maps, stability analyses, socio-economic cost analyses and other influential factors.

CONCLUSIONS

The presented methodology is considered suitable for Brza voda watershed. It certainly can be considered as one of the possible approaches, and we can recommend it for the level of feasibility studies. General conclusion is that the presented risk assessment method is an iterative process, which can be adjusted for other similar problems. Adjustments will depend on the specifics of each analyzed area. The importance of the geotechnical aspect is clearly visible, but this aspect shall be considered as only one link in the chain of factors in the whole system. Nevertheless, the presented methodology is "easy" and "simple" to be used by different stakeholders and municipalities, despite some limitations and uncertainties. This is also, an open field for further scientific and practical analyses.

ACKNOWLEDGMENT

The author's express gratitude for the support by ROCSCIENCE Company, for using the software in educational and scientific purposes, as well as to UNDP because the project is funded a part of the wider project with a title "Feasibility Study on Basin Scale Sediment Management Options for the Polog Region number 41/2019 55510".

REFERENCES

1. Andersson YS, Falemo S, Tremblay M. (2014) Development of methodology for quantitative landslide risk assessment – example Göta river valley. Natural Science, doi:10.4236/ns.2014.63018.
2. Jovanovski M, Peshevski I, Papic J, Nedelkovska N, Gorgiev G, Peduto D. (2021a) Feasibility Study on Basin Scale Sediment Management Options for the Polog Region. 2021; United Nations Development Program Skopje.
3. Jovanovski M, Peshevski I, Gorgiev G, Nedelkovska N, Nicodemo G, Reale D, Fornaro G, Peduto D. (2021b) Landslide characterization in the Polog region by innovative and conventional methods. Italian Geotechnical Journal. 2021; 4:5–29.
4. Nedelkovska N. (2023) Contemporary methods for detection and characterization of terrain unstable phenomena, Doctoral dissertation, University Ss. Cyril and Methodius in Skopje, Faculty of Civil Engineering, Skopje
5. Nedelkovska, N., Peshevski, I., Jovanovski, M. (2017). Methodology for preparation of thematic geotechnical maps for urbanisation purposes using polynomial interpolation method. Науката Будіництво 3 (13), pp. 27-31.
6. Peshevski I. (2015) Modeling of landslide susceptibility using GIS technologies. Ph.D. thesis, Faculty of Civil Engineering, Skopje (in Macedonian).
7. Skempton AW, Delory FA (1957) Stability of natural slopes in the London clay. Proc. of the Fourth Int. Conf. on Soil Mech. 1957; v. II, P. 378-381.
8. Van Westen CJ, Terlien T J.(1996) An approach towards deterministic landslide hazard analysis in GIS: a case study from Manizales (Colombia). Earth Surface Processes and Landforms. 1996; 21(9):853–868.