ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20230425115933

Original scientific paper
Received: 2023-04-25, Accepted: 2024-01-18

Soil Erosion Susceptibility Prediction Using GIS-Based Multicriteria Analysis and Worldview-3 Satellite Images

Ante Šiljeg, Mladen Jurišić, Ivan Marić, Fran Domazetović, Dorijan Radočaj*

Abstract: Soil erosion has been identified as a major threat to existing soil deposits, which negatively affects ecosystem sustainability, agricultural production and clean water supply. This study covered the eastern part of Kaštela Bay with the aim of developing a model of susceptibility to soil erosion by applying the GIS-based multicriteria analysis, based on nine determinant criteria categorized by the Jenks method in five classes. The largest representation of soil erosion susceptibility was detected on the slopes of the Kozjak and Mosor massifs. According to the calculated weighting coefficients using the analytic hierarchy process (AHP), the slope was the most impactful criterion with 29.9 % importance. It was followed by hydrological criteria of topographic wetness index, standardized precipitation index and LS-factor, with 13.1 % importance each. After the development of the model, zones of very high and high susceptibility to soil erosion were delineated, with a combined coverage of 33.34 % of the study area. These areas were identified as a potential threat from the future occurrence of negative effects of soil erosion, which should be addressed in the future by land policy managers and government managers.

Keywords: analytic hierarchy process (AHP); digital elevation model; GAMA method; GIS-based multicriteria analysis; soil erosion

1 INTRODUCTION

Soil erosion is a process of gradual degradation and denudation of surface soil layers, which globally causes long-term reductions in agricultural productivity and significant financial losses [1]. It has been identified as a major threat to existing soil deposits, which negatively affects ecosystem sustainability, agricultural production and clean water supply [2]. Although soil erosion is a natural process, rapid climate change (desertification, extreme rainfall, heat waves) and various anthropogenic pressures (deforestation, overgrazing, inappropriate agricultural practices and tillage) recently intensified and expanded the spatial scope of this process [1]. Historical sources from different parts of the world noted that soil erosion was present throughout almost the entire Holocene, and that climate change and anthropogenic effects gradually became the main propagators of this process. Land use has a significant impact on the geomorphological stability of the slope and the emergence of various slope processes. Improper land use, such as excessive deforestation or livestock valorization of a particular area, can significantly accelerate the natural process of soil erosion [3]. Resistance to wear processes is related to vegetation cover and the approach a particular location is utilized. Vegetation cover has a diminishing effect on the susceptibility of a particular terrain to soil erosion, as it reduces the erosive ability of surface runoff [4].

According to the average rate of soil loss, Croatia is among the most endangered countries of the European Union [2]. However, some parts of Croatia are significantly more vulnerable and endangered than the soil erosion process due to different micro-location characteristics, with very high values of the average loss rate. Particularly high values of the average rate of soil loss are present in the coastal area. The development of a model of susceptibility to soil erosion is the basis for planning measures to limit and adapt to further negative consequences of the soil erosion process. With the application of GIS-based multicriteria decision analysis (GIS-MCDA), it is possible to develop a model of soil susceptibility to soil erosion according to appropriate predisposing criteria, such as slope, aspect, planar and profile curvature. Due to the pronounced influence of slope on the evolution of relief, it has a decisive role in the development of a model of susceptibility to soil erosion [4]. The terrain aspect can indirectly affect the intensity of soil erosion, determining the effects of climatic factors, such as sunshine duration, precipitation intensity, humidity, wind exposure and conditions the development of vegetation cover [4]. Terrain curvature affects the soil-water interaction during surface runoff, but also the rate of water runoff down the slope [5].

The aim of the research is to develop a model of susceptibility to soil erosion of the wider eastern part of Kaštela Bay through the application of GIS-MCDA and to identify areas of a potential threat from the future occurrence of negative effects of soil erosion.

2 MATERIALS AND METHODS

The study area covers a wider eastern part of the Kaštela Bay, which is historically among the most susceptible areas to soil erosion in Croatia (Fig. 1). The development of a model of susceptibility to soil erosion was carried out through the application of GIS-MCDA. Its application in soil erosion modeling consisted of six steps, three of which are automated using the GIS automated multicriteria analysis (GAMA) method [6]. GIS-MCDA analysis was performed based on nine determinant criteria and zones with different susceptibility to soil erosion were selected. The resulting zones were categorized by the Jenks natural breaks classification method in five classes, minimizing deviation of values within the class according to class mean (very low, low, medium, high and very high susceptibility).

Criteria extracted from the digital elevation model (DEM) were divided into primary and secondary morphometric parameters. As the input in GIS-MCDA, the following primary morphometric parameters were singled out: slope, aspect, planar and profile curvature. The three secondary parameters representing hydrological effects were topographic wetness index, standardized precipitation index, specific watersheds, and one morphometric secondary parameter (LS-factor). Figs. 2 and 3 display selected primary and secondary criteria for GIS-MCDA susceptibility to soil erosion.

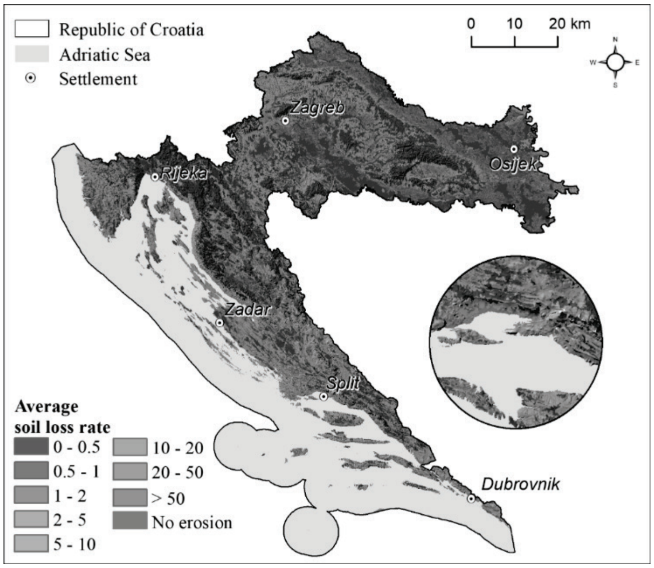

Figure 1 Study area with average annual soil loss rate in Croatia, based on data from Panagos et al. (2015) and ESDAC (2020)

The digital surface model (DSM) is created from the provided WV-3 stereo images in the OrthoEngine 2018 extension of the Geomatica 2018 software. DSM was created in the OrthoEngine extension is divided into selecting a mathematical model, adding orientation and control points needed for the orientation of stereo images, automatically adding of tie points, adjusting the model (bundle adjustment), making an epipolar image, automatically creating a DSM, and manual error filtering. Optical Satellite modeling based on assigned rational polynomial coefficients (RPC) and zero-order polynomial adjustment was selected as the most commonly used mathematical models for DSM creation from WV stereo images [7].

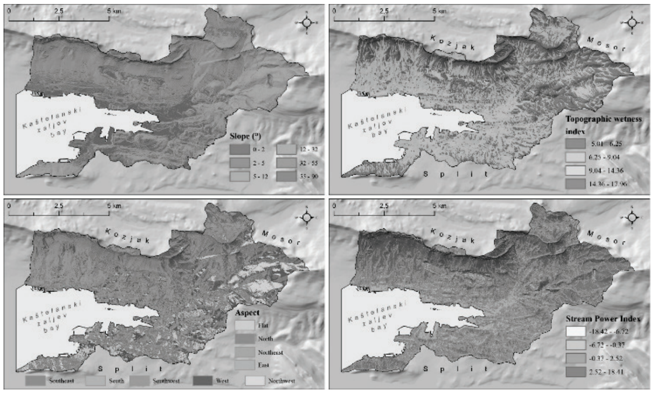

Figure 2 Selected primary criteria for GIS-MCDA susceptibility to soil erosion

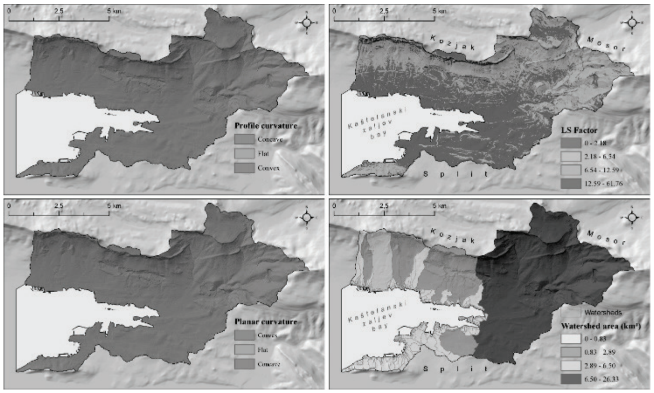

Figure 3 Selected secondary criteria for GIS-MCDA susceptibility to soil erosion

Field orientation points with precise coordinates for DSM georeferencing were collected on May 12, 2020 with *Stonex S10* real-time-kinematic (RTK) global navigation satellite system (GNSS) receiver, at 13 different locations distributed throughout the research area. The method of semi-global matching of DSM was used. Automatic DSM correction to digital terrain model (DTM) was performed by Geomatica 2018 software using the DSM2DTM algorithm, which allowed automatic DSM filtering according to defined user-defined parameters. After automatic conversion by manual filtering, all remaining errors which arose from the automatic filtration process were removed.

By standardizing the selected GIS-MCDA criteria, all input values are transformed to an equal numerical scale through a process of criteria standardization [8]. The used nine criteria were standardized on a numerical scale of 1–5 using the GAMA method, so that value of 1 was assigned to the least suitable class, while the value of 5 was assigned to the most suitable class per criterion. The Boolean criteria were assigned with binary values of 0 or 1. The analytic hierarchy process (AHP) was used for weight determination of input criteria, which allowed the subjectivity and consistency of weight coefficients to be verified through a consistency ratio (CR) [9]. The aggregation of standardized criteria values and their respective weighting coefficients was performed using the weighted linear combination.

3 RESULTS AND DISCUSSION

The susceptibility model to soil erosion was performed in six steps through the application of GIS-MCDA in ArcGIS software. Susceptibility to soil erosion according to the representation of individual classes is shown in Tab. 1. According to the results of the representation of individual classes of susceptibility to soil erosion in Tab. 1, it was observed that the Boolean criterion occupies the largest area. The Boolean criterion includes all permanent water surfaces as well as all urban and industrially built areas, in which due to anthropogenic modifications of the terrain, soil erosion cannot occur. These areas are excluded from the GIS-MCDA of soil erosion susceptibility as areas with no probability of soil erosion, with a weighting factor of zero. An overview of the AHP pairwise comparison matrix is shown in Tab. 2, and the calculated weighting coefficients are shown in Tab. 3.

Table 1 Representation of individual classes of susceptibility to soil erosion

Susceptibility class	Area (km²)	Share (%)
Boolean	20.12	27.58
Very low	6.98	9.56
Low	9.94	13.62
Medium	11.61	15.91
High	14.98	20.52
Very high	9.35	12.81

Table 2 Pairwise comparison matrix of criteria within the AHP

Criterion	SLO	TWI	SPI	LSF	ASP	LULC	PROF	PLAN	WAT
SLO	1	3	3	3	3	4	6	6	9
TWI		1	1	1	2	2	3	3	6
SPI			1	1	2	2	3	3	6
LSF				1	2	2	3	3	6
ASP					1	3	5	5	6
LULC						1	3	3	6
PROF							1	1	3
PLAN								1	1
WAT									1

SLO: slope, ASP: aspect, PLAN: planar curvature, PROF: profile curvature, TWI: topographic wetness index, SPI: standardized precipitation index, WAT: specific watersheds, LSF: LS-factor

Table 3 Weighting coefficients representing the impact of individual criteria on soil erosion susceptibility calculated within the AHP

Criterion	Weighting coefficient	Share (%)
SLO	0.299	29.9
TWI	0.131	13.1
SPI	0.131	13.1
LSF	0.131	13.1
ASP	0.125	12.5
LULC	0.082	8.2
PROF	0.041	4.1
PLAN	0.041	4.1
WAT	0.019	1.9

SLO: slope, ASP: aspect, PLAN: planar curvature, PROF: profile curvature, TWI: topographic wetness index, SPI: standardized precipitation index, WAT: specific watersheds, LSF: LS-factor

According to the results in Tab. 3, the largest percentage is occupied by terrain slope, which according to Wilson and Gallant [10] directly affects the intensity of various denudation processes. Due to the pronounced influence of slope on the evolution of relief, the slope criterion has a decisive role in the development of a susceptibility model to soil erosion [4]. The second factor that had the greatest impact on soil erosion susceptibility was the aspect, as it indirectly affects soil erosion intensity and determines the susceptibility to climatic factors [11]. Among the lower impacts, the profile and planar curvature of the slope were observed, since on convex slopes the surface runoff slows down and the transport capacity weakens. Specific watersheds had the least impact on soil erosion. The consistency of pairwise comparison matrix in AHP was checked through a CR of 0.046. Based on the developed model of susceptibility to soil erosion of the wider eastern part of the Kaštela Bay (Fig. 4), zones of a potential threat from the future occurrence of negative effects of soil erosion have been identified.

As displayed in the developed susceptibility model within the wider eastern part of Kaštela Bay, very high and high zones of susceptibility prevail, covering 33.34 % of the total study area. Their dominant concentration was detected on the slopes of the Kozjak and Mosor massifs. On these slopes, water runoff occurs from a larger area, where in some locations there may be a gradual formation of more pronounced surface runoff and soil erosion. This is in line with the observations of Valentin et al. [3], where the velocity and erosive force of runoff increased according to the increase in slope. This area is also affected by the recent intensive urbanization, but also by agricultural valorization and exploitation of mineral raw materials for cement production, such as exploitation field "St. Juraj - St. Kajo" [12]. These anthropogenic factors affect the acceleration of the natural intensity of soil erosion, contributing to an increase in susceptibility to the emergence of new erosion zones [13]. Low and very low susceptibility to soil erosion are also present on bare slopes in the peak zone of Kozjak and Mosor, where the configuration of the relief prevents the formation of more prominent surface runoff. Zones of very low susceptibility cover a total of 6.98 km² (9.56% of the total area), while zones of low susceptibility cover 9.94 km², or 13.62% of the total area of the study area. The coastal area is generally a flat and densely populated area, where susceptibility to soil erosion is very low. A large part of this area is covered by anthropogenic substrates like concrete or asphalt, which prevent soil erosion. The zone of medium susceptibility to soil erosion covers 15.91% of the total area of the research area, which mainly refers to the transition area between the flat coastal area and the steeper slopes of Kozjak and Mosor.

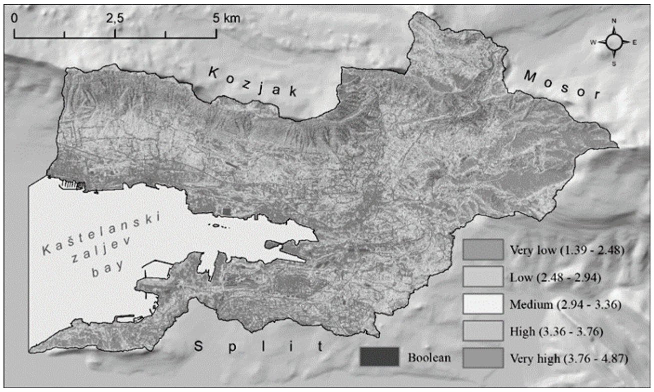

Figure 4 Susceptibility model to soil erosion of the wider eastern part of the Kaštela Bay

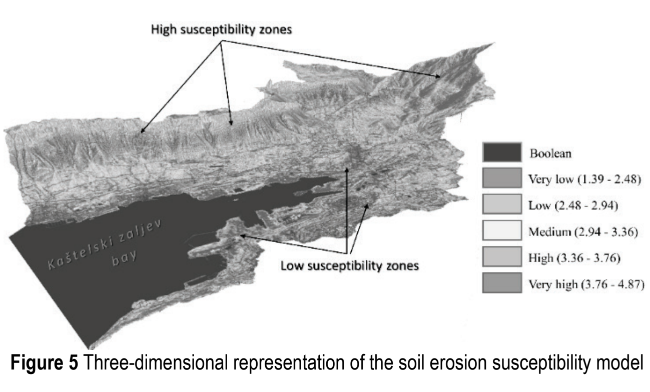

Figure 5 Three-dimensional representation of the soil erosion susceptibility model

Based on the 3D representation of the developed susceptibility model to soil erosion (Fig. 5), it can be further confirmed that most of the zones of greatest susceptibility to soil erosion are located on the slopes of Kozjak and Mosor. In addition, it is evident that the zones of least susceptibility to soil erosion are located mainly in the area of flat coastal areas. This points out to the possibility of improper land use, caused by anthropogenic activities of deforestation or livestock valorization, which can significantly accelerate the natural process of soil erosion. Conversely, the importance of digital soil mapping for other biochemical and physical properties [14] and infiltration modelling [15] arouse, aiding land policy managers in more sustainable management.

4 CONCLUSIONS

Based on the developed susceptibility model to soil erosion using GIS-MCDA of the wider eastern part of Kaštela Bay, potential zones of threat from the future occurrence of negative effects of soil erosion have been successfully identified. The slope had the largest impact on soil erosion and occupied the largest area of the study area, while the specific watersheds had the smallest impact. The developed model of susceptibility within the investigated area is primarily affected by zones of very high and high susceptibility to soil erosion, which together covers 33.34 %. By making a 3D representation of the susceptibility to soil erosion, it was determined that most of the zones with the greatest susceptibility to soil erosion are located on the slopes of Kozjak and Mosor. Zones of the least susceptibility to soil erosion were observed mainly in the area of flat coastal areas, which should be addressed in the future by land policy managers and government managers. These findings not only contribute to a comprehensive understanding of soil erosion dynamics in the region but also provide valuable information for effective land management and conservation strategies to mitigate the impending environmental challenges associated with soil erosion.

Acknowledgements

Data in this research were collected within the PEPSEA Split and STREAM projects. The findings and results of this paper will be used for the STREAM (Strategic Development of Flood Management) project.

5 REFERENCES

[1] Borrelli, P., Robinson, D. A., Fleischer, L. R., et al. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature communications*, *8*(1), 2013. https://doi.org/10.1038/s41467-017-02142-7

[2] Panagos, P., Ballabio, C., Borrelli, P., et al. (2015). Rainfall erosivity in Europe. *Science of the Total Environment*, *511*, 801-814. https://doi.org/10.1016/j.scitotenv.2015.01.008

[3] Valentin, C., Poesen, J. & Li, Y. (2005). Gully erosion: Impacts, factors and control. *Catena*, *63*(2-3), 132-153. https://doi.org/10.1016/j.catena.2005.06.001

[4] Conforti, M., Aucelli, P. P., Robustelli, G. & Scarciglia, F. (2011). Geomorphology and GIS analysis for mapping gully erosion susceptibility in the Turbolo stream catchment (Northern Calabria, Italy). *Natural hazards*, *56*, 881-898. https://doi.org/10.1007/s11069-010-9598-2

[5] Agnesi, V., Angileri, S., Cappadonia, C., Conoscenti, C. & Rotigliano, E. (2011). Multi parametric GIS analysis to assess gully erosion susceptibility: A test in southern Sicily, Italy. *Landform Analysis*, *17*, 15-20. https://doi.org/10.1016/j.geomorph.2013.08.021

[6] Domazetović, F., Šiljeg, A., Lončar, N. & Marić, I. (2019). GIS automated multicriteria analysis (GAMA) method for susceptibility modelling. *MethodsX*, *6*, 2553-2561. https://doi/org/10.1016/j.mex.2019.10.031

[7] Aguilar, M. Á., del Mar Saldaña, M. & Aguilar, F. J. (2013). Generation and quality assessment of stereo-extracted DSM from GeoEye-1 and WorldView-2 imagery. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(2), 1259-1271. https://doi.org/10.1109/tgrs.2013.2249521

[8] Feizizadeh, B. & Blaschke, T. (2013). GIS-multicriteria decision analysis for landslide susceptibility mapping: comparing three methods for the Urmia lake basin, Iran. *Natural hazards*, *65*, 2105-2128. https://doi.org/10.1007/s11069-012-0463-3

[9] Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. *European journal of operational research*, *48*(1), 9-26. https://doi.org/10.1016/0377-2217(90)90057-I

[10] Wilson, J. P. & Gallant, J. C. (2000) Digital terrain analysis. Terrain analysis: *Principles and applications, 6*(12), 1-27.

[11] Rahmati, O., Haghizadeh, A., Pourghasemi, H. R. & Noormohamadi, F. (2016). Gully erosion susceptibility mapping: the role of GIS-based bivariate statistical models and their comparison. *Natural Hazards*, *82*, 1231-1258. https://doi.org/10.1007/s11069-016-2239-7

[12] Bralić, N. & Malvić, T. (2022). Cement raw material reserve calculation—geological sections vs. structural maps approaches, case study from Southern Croatia. *Minerals*, *12*(8), 1056. https://doi.org/10.3390/min12081056

[13] Li, P., Chen, J., Zhao, G., Holden, J., Liu, B., Chan, F. K. S., ... & Mu, X. (2022). Determining the drivers and rates of soil erosion on the Loess Plateau since 1901. *Science of the Total Environment*, *823*, 153674. https://doi.org/10.1016/j.scitotenv.2022.153674

[14] Radočaj, D., Tuno, N., Mulahusić, A. & Jurišić, M. (2023). Evaluation of Ensemble Machine Learning for Geospatial Prediction of Soil Iron in Croatia. *Poljoprivreda*, *29*(2), 53-61. https://doi.org/https://doi.org/10.18047/poljo.29.2.7

[15] Šiljeg, A., Panđa, L., Marinović, R., Krvavica, N., Domazetović, F., Jurišić, M. & Radočaj, D. (2023). Infiltration Efficiency Index for GIS Analysis Using Very-High-Spatial-Resolution Data. *Sustainability*, *15*(21), 15563. https://doi.org/10.3390/su152115563

Authors' contacts:

Ante Šiljeg, PhD, Associate Professor
University of Zadar, Department of Geography,
Trg kneza Višeslava 9, 23000 Zadar, Croatia
asiljeg@unizd.hr

Mladen Jurišić, PhD, Full Professor
Faculty of Agrobiotechnical Sciences Osijek,
Vladimira Preloga 1, 31000 Osijek, Croatia
mjurisic@fazos.hr

Ivan Marić, PhD, Assistant Professor
University of Zadar, Department of Geography,
Trg kneza Višeslava 9, 23000 Zadar, Croatia
imaric1@unizd.hr

Fran Domazetović, PhD, Assistant Professor
University of Zadar, Department of Geography,
Trg kneza Višeslava 9, 23000 Zadar, Croatia
fdomazeto@unizd.hr

Dorijan Radočaj, PhD
(Corresponding author)
Faculty of Agrobiotechnical Sciences Osijek,
Vladimira Preloga 1, 31000 Osijek, Croatia
dradocaj@fazos.hr