DOI: https://doi.org/10.17721/2306-5680.2022.4.2
UDC 556.537:551.4

Szatten D., Herman O., Tęgowska N.
Kazimierz Wielki University, Poland

FUNCTIONALITY OF SPATIAL ANALYSIS IN THE ASSESSMENT OF THE IMPACT OF LAND COVER ON THE EROSION PROCESS PREDICTION

Erosion is a process shaping the earth's surface, responsible for supplying sediment to the fluvial system. Identification of areas vulnerable to erosion is a critical element of sediment management in the catchment, enabling the assessment of the degree of its degradation. The research was based on the use of spatial data, Digital Terrain Model (DTM), and Corine Land Cover (CLC) on the example of two sub-catchments located on the lower Brda River. The main aim of the research was to assess the impact of land cover on the spatial prediction of the erosion process at the catchment scale. The Maximum Entropy Method was used to determine the spatial probability distribution of environmental variables related to the erosion process. Results showed the greatest predictive power of relief-related environmental features, associated with specific types of land cover. Predictive models can be successfully used to predict areas potentially exposed to erosion.

Keywords: *erosion; Maximum Entropy Model; prediction; Corine Land Cover (CLC); spatial analyses; Brda River catchment*

Introduction. As is commonly known, erosion is a natural process that modifies the relief of the Earth surface. The second component of the changes is the transformations of the terrain resulting from human activity. Erosion and sediment yield depend on several factors, related to geological, lithological, topographic, climatic, etc. conditions (Guerra et al., 2017). Hydrological responses related to erosion processes in the catchment scale also depend on land use and vegetation (Siriwardena et al., 2006). Understanding the erosion process enables sustainable sediment management at the catchment scale.

Geographic Information Systems (GIS) tools enable remote control of environmental processes, including the erosion process. In addition, the use of models enables a better understanding and forecasting of processes taking place in the environment. Soil erosion prediction models are classified into two groups: empirical and physical process-based models. The most commonly used are The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), and Erosion Potential Method (EPM) (Amiri, 2010), etc. They achieve the best results on small scales, while their wider application for large areas is difficult (Merritt et al., 2003). Stochastic models based on presence/absence factors with environmental variables are not commonly used in erosion process research. It is a user-friendly tool, using the ROC (receiver operating characteristics) curve, enabling the study of a large area in a relatively quickly.

The main aim of the research was to assess the impact of land cover on the prediction of the erosion process on the example of two sub-catchments of the lower Brda River. In the research, spatial data were used: a Digital Terrain Model (DTM), and a database of the European land cover system - Corine Land Cover (CLC). The primary research hypotheses were: (i) relief in connection with the type of land cover, mainly determines the probability of the erosion process, (ii) local conditions strongly modify the sources of supply, transport paths, and deposition of eroded sediment in the catchment; (iii) predictive models enable a qualitative assessment of the erosion process at the catchment scale. To verify the assumed hypotheses, the Maximum Entropy Model tool was used, to determine the predictive power of environmental variables. The conducted research is significant from the point of view of the possibility of using new tools in the qualitative determination of the circulation of sediment in the catchment scale.

Study area. The Brda River catchment amounts to 4661 km^2 and a length of 245 km (Map, 2007), which is a lowland tributary of the Vistula River (Poland). The geomorphological genesis of the catchment is related to the accumulation stage of the last glaciation (Galon, 1953). The Brda valley is built of different-grained sands, surrounded by moraine uplands. The Brda River catchment is intense modified by hydrotechnical structures: dams – Mylof Reservoir in the middle course of the river, and Lower Brda Cascade (Koronowo, Tryszczyn, Smukała reservoirs) in the lower course (Szatten et al., 2018). At the same time, the hydrological regime of the estuary section of the Brda River, due to hydrotechnical works started in the Middle Ages - weirs, sluices, and canalization, is strongly transformed (Szatten, 2022).

The study area is two sub-catchments located in the lower part of the Brda River. Considering the physical-geographical regionalization of Poland (Solon et al., 2018), the Z1 catchment is located in the Southern Pomerania Lakeland macroregion (314.6-7), on the border of two mesoregions: Southern Krajna Lakeland (314.74) (western part), and the Brda River Valley (314.72) (eastern part). However, the catchment area Z2 is located within the Southern Pomerania Lakeland macroregion (314.6-7) (the northern part of the catchment), the mesoregions: Brda River Valley (314.72) and Świecie Upland (314.73), and the Toruń-Eberswalde Ice Marginal Valley macroregion (315.3), mesoregion Toruń Basin (315.35). Their choice results from intense morphometric and land cover diversity. In the case of the C1 catchment, 9 types of land cover were distinguished, while in the C2 catchment, 15 types of CLC were defined (Figure 1). The C1 catchment area – Brda River below the Koronowo Reservoir, amounts to 29.38 km^2. The area is dominated by non-irrigated arable land (type CLC 2.1.1) covering 20.31 km^2 of the catchment area (69%). The C2 catchment area – the estuary part of the river within the city of Bydgoszcz, amounts to 111.79 km^2. The land cover of this catchment is dominated by coniferous forest (type CLC 3.1.2) 42.91 km^2 (38%), and discontinuous urban fabric (type CLC 1.1.2) 24.33 km^2 (22%) (Fig. 1).

A B

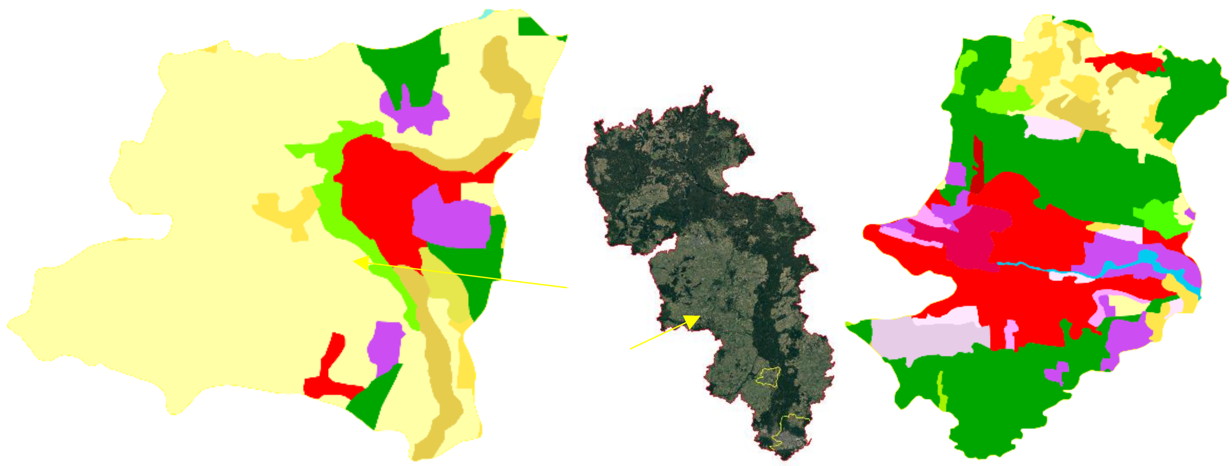

Fig. 1. **Corine Land Cover (CLC) of the Brda River sub-catchment area: C1 (A), and C2 (B).**

Materials and methods. The input data was a Digital Terrain Model (DTM) obtained from the resources of the Head Office of Geodesy and Cartography in Poland. Data in ASCII format file in the 1992 coordinate system, with a horizontal resolution of 1 x 1 m, and a vertical pixel accuracy of 0.1-0.25 m. The Corine Land Cover 2018 data was obtained from the resources of the Copernicus Land Monitoring Service (CLMS). According to technical assumptions, CLC uses a Minimum Mapping Unit of 25 ha for area phenomena and a minimum width of 100 m for linear phenomena (Heymann, 1994).

Spatial analyzes in QuantumGIS (v.3.4.12), and SAGA software (Conrad et al., 2015) were performed. Based on the Map of the hydrological division of Poland (2007), a sub-catchment for further research was identified. DTM was preprocessed using the Fill Sink formula (Planchon and Darboux, 2002), and then selected geoprocessing tools to determine 4 basic spatial parameters were used: LS-Factor - LSF (Moore et al., 1991), Melton Ruggedness Number - MRN (Marchi and Fontana, 2005), Stream Power Index - SPI (Moore et al., 1991) and Topographic Wetness Index - TWI (Sørensen et al., 2005).

The spatial probability distribution for the four environmental variables for the analyzed sub-catchments was determined using the Maximum Entropy Method (Phillips et al., 2006). The method is based on the Gibbs distribution and has been successfully used in environmental research (Kornejady et al., 2017; Bosino et al., 2020; Szatten and Więcław, 2021; Brzezińska et al., 2021). The dependent variables for the two studied sub-catchments were 10,000 random presence/absence background points, according to the basis defined by Phillips and Dudik (2008). The model was randomly validated, using it as a training sample (80% of data) and test sample (20% of data). The results define the percentage share of environmental variables in the model, using the AUC (area under curve) values, which determine the model's effectiveness. According to the criterion introduced by Hosmer and Lemeshow (2000), AUC>0.7 indicates acceptable model results, 0.8<AUC<0.9 indicates an excellent probability, and AUC>0.9 indicates an outstanding prediction.

Results and discussion. Results of spatial analyses of environmental variables allow for characterizing the study area in terms of the erosion process. The first one, the slope-length factor (LSF) is a commonly used indicator of erosion, proposed by Wischmeier and Smith (1978) in the USLE model. For C1 it assumes values in the range from 0.00 to 7.22 (average 0.29), and for C2 in the range from 0.00 to 18.49 (average 0.17). In the case of both analyzed catchments, the LSF maximum values are related to the area of the river valley edges, for C1 - the Brda River valley, and for C2 - the marginal zone of the moraine plateau (Fig. 2). A similar spatial distribution for the second analyzed index MRN (Fig. 2) is observed. Index described a flow accumulation index, related to terrain relief (Melton, 1965). For C1 it assumes values in the range from 0.00 to 2.75 (average 0.21), and for C2 in the range from 0.00 to 2.39 (average 0.28). The research of Saha et al. (2019) also shows that relief variability is strongly related to susceptibility to soil erosion in the catchment. The next indicator is SPI, which determines the erosive power of flowing water (Moore et al., 1991). For C1 it assumes values in the range from 0 to 45979 (average 796), and for C2 in the range from 0 to 171003 (average 41). Linking the value of the SPI with the water surface slope makes it possible to characterize the ability to sediment transport, indicating that C2 has a much lower potential (Fig. 2), due to the regulated - canalized water regime of the river channel (Szatten, 2016). The SPI index was also included in the research of Pournader et al. (2018), where the prediction results of the Maximum Entropy Method indicated it as significant in the preparation of erosion susceptibility maps. The last indicator – TWI describes a potential generation of runoff (Sørensen et al., 2005) and indicates a potential area of sedimentation. This indicator has been successfully used in determining the potential erosive power of the surface runoff in the small catchment (Bosino et al., 2022). For C1 it assumes values in the range from 5.29 to 20.88 (average 9.46), and for C2 in the range from 4.49 to 23.17 (average 10.21). The spatial distribution of the maximum TWI values for the C1 catchment indicated the upper areas as potential areas of supply of eroded sediment, and the bottom of the Brda River valley as an area of sediment accumulation (Figure 2). However, in the case of the C2 catchment, the environmental variable indicated the potential path of the sediment transport associated with surface runoff (Fig. 2).

Depending on the type of CLC, the percentage share of the tested environmental parameters in the Maximum Entropy Model had a unique distribution. The dominant environmental variable identified by the model was the MRN for both analyzed catchments (Fig. 3). Depending on the type of CLC, the maximum percentage in the model was 88.01% for CLC 2.1.1 (catchment C1), and 96.59% for CLC 3.2.4 (catchment C2). The average MRN value in the model was 49.03% for the C1 catchment, and 63.81% for the C2 catchment. The other three environmental variables had significantly smaller contributions to the model results (Fig. 3). The average model shares for LSF, SPI, and TWI were respectively 19.70% (C1) and 12.62 (C2), 11.66% (C1) and 9.28% (C2), 19.61% (C1) and 14.29% (C2).

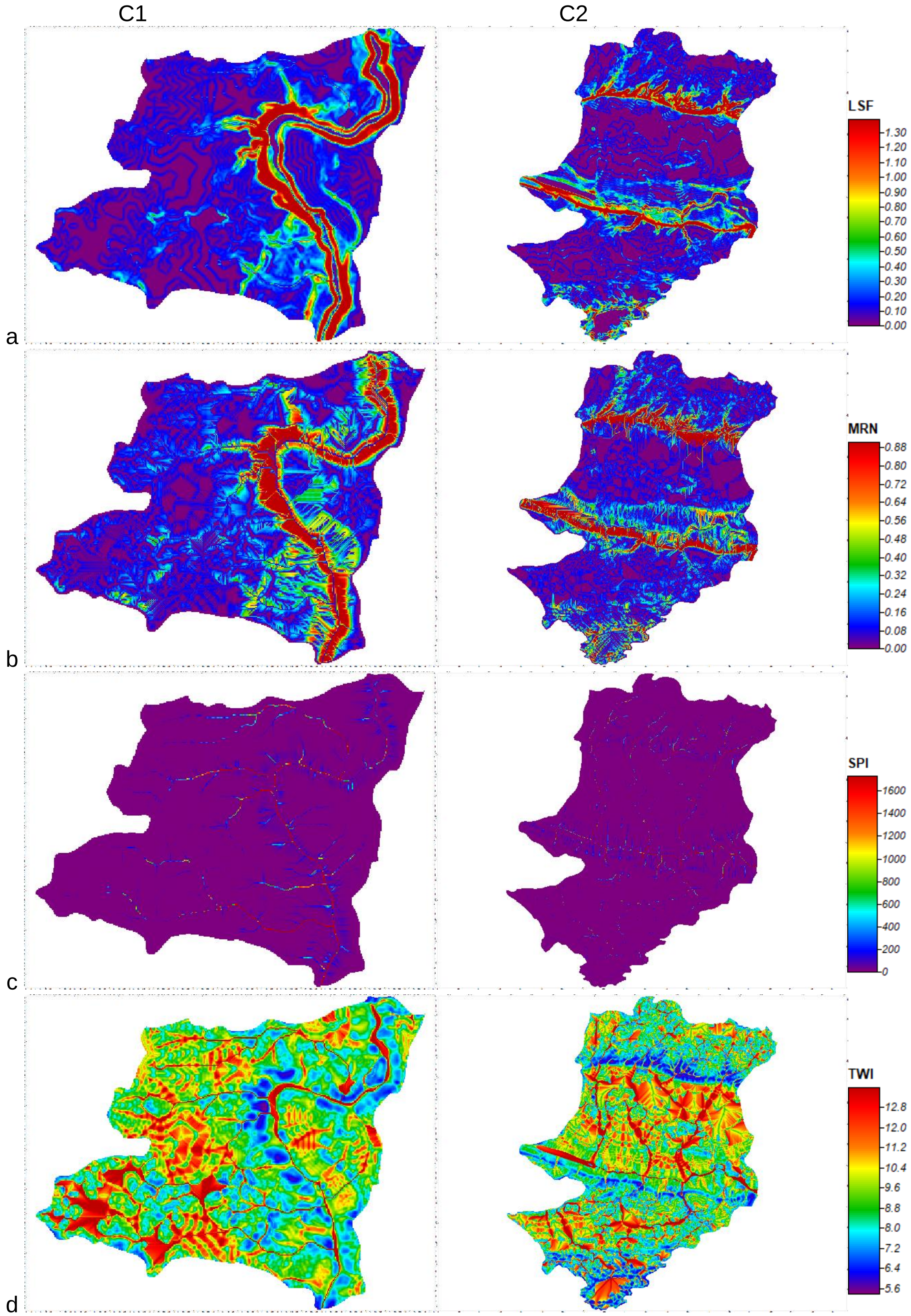

Fig. 2. **The spatial image of morphometric characteristics of the study area catchment: C1, C2 – analyzed sub-catchments; a – LSF, b – MRN, c – SPI, d - TWI.**

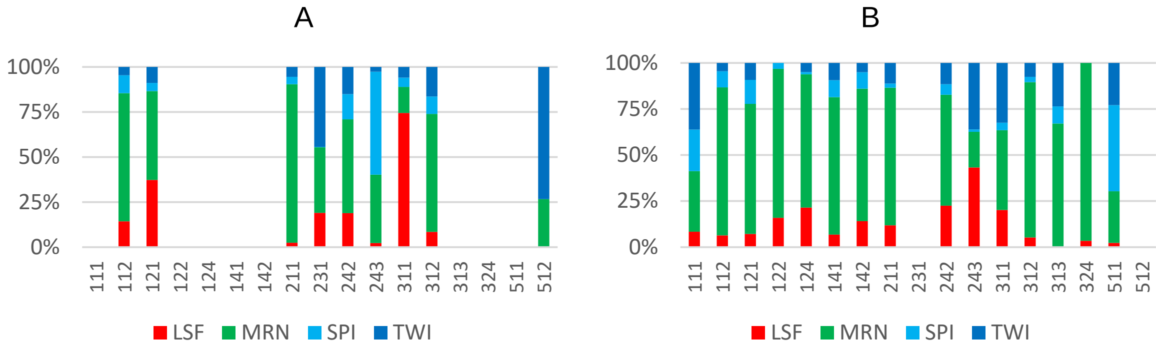

Fig. 3. **Percentage of the dominant parameter in Maximum Entropy Model in the examined sub-catchments (C1 - A, and C2 - B) for selected CLC types.**

In the case of the C1 catchment, the spatial distribution of the model results indicates that the areas with AUC>0.9 are the edge zone of the Brda River valley (type CLC 3.1.1), and the fragmentarily sandur area (type 2.3.1) (Fig. 4). The total area of the C1 catchment corresponding to the value of AUC>0.9 is 0.64 km^2. Areas with lower predictive power (0.7<AUC<0.9) are unevenly distributed for other types of CLC, most concentrated for CLC 2.4.3 located in the bottom of the Brda River valley.

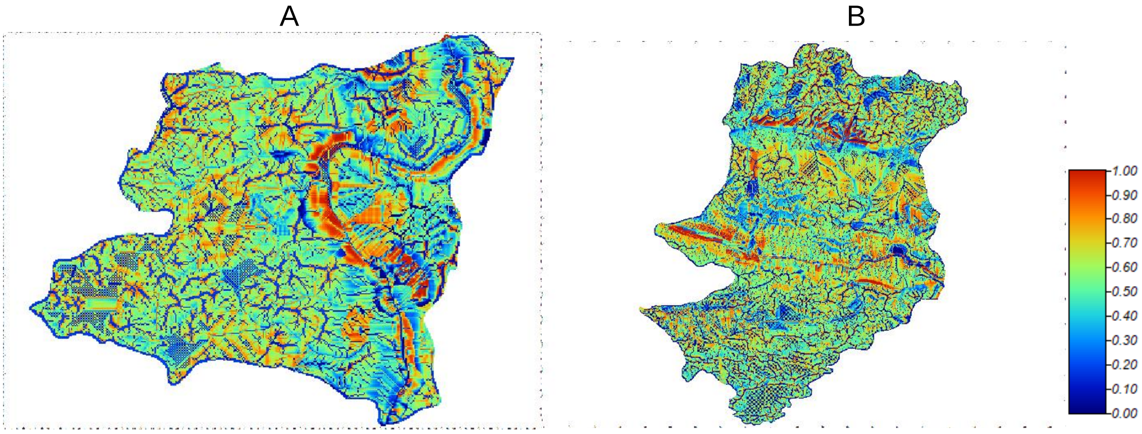

Fig. 4. **Spatial differentiation of AUC values for Maximum Entropy Model in examined catchments: A – C1, B – C2.**

For the C2 catchment, the spatial distribution of the model results indicates that the areas with AUC>0.9 are fragmentary edge zone (southern) of the moraine plateau (type CLC 1.4.1), fragmentary edge zone (north) of the moraine plateau (type 2.4.3) and partly the edge zone (northern) moraine plateau covered by forest (type 3.1.1) (Fig. 4). The total area of the C2 catchment corresponding to the value of AUC>0.9 is 2.56 km^2. Areas with lower predictive power (0.7<AUC<0.9) are unevenly distributed for the remaining types of CLC, most concentrated within the narrow valley of the Brda River.

Conclusion. Based on the results of the conducted research on the assessment of the impact of the catchment area land cover on the prediction of the erosion process, using the Maximum Entropy Method, the following conclusions can be drawn:

1. The lithological, and hydrological characteristics of the catchment determine its erosion potential to a large extent. In the case of the studied catchments, the diversification of the terrain relief showed the highest predictive power in the model. Among the studied indicators, the MRN showed a positive correlation with the potential sources of sediment supply from the catchment. The impact of local morphological conditions of the catchment, which intense modify the sources of supply, transport paths, and deposition, should be taken into account.
2. The modeling results related to the types of CLC: 1.4.1, 2.3.1, 3.1.1, link with the local characteristics of the independent environmental variables (LSF, MRN, SPI, TWI) showed the highest predictive power, illustrated by the value of AUC>0.9.

3. The conducted research showed the need to implement predictive models, including the Maximum Entropy Method, in the qualitative assessment of the erosion process and the circulation of sediments at the catchment scale. These tools can be successfully used to predict areas potentially exposed to denudation, considering the variable land cover, to determine the directions of anti-erosion protection in the catchment. It is a tool for sustainable sediment management in the catchment.

References

1. *Amiri, F*. Estimate of erosion and sedimentation in semi-arid basin using empirical models of erosion potential within a geographic information system. Air Soil and Water Res. 2010, 3, 37.

2. *Bosino, A.; Giordani, P.; Quénéhervé, G.; Maerker, M.* Assessment of calanchi and rill–interrill erosion susceptibilities using terrain analysis and geostochastics: A case study in the Oltrepo Pavese, Northern Apennines, Italy. Earth Surf. Process. Landf. 2020, 45, 3025–3041.

3. *Bosino, A.; Szatten, D.; Omran, A.; Crema, S.; Crozi, M.; Becker, R.; Bettoni, M.; Schillaci, C.; Maerker, M.* Assessment of suspended sediment dynamics in a small ungauged badland catchment in the Northern Apennines (Italy) using an in-situ laser diffraction method, Catena 2022, 209 (1), 105796.

4. *Brzezińska, M.; Szatten, D.; Babiński, Z.* Prediction of Erosion-Prone Areas in the Catchments of Big Lowland Rivers: Implementation of Maximum Entropy Modelling—Using the Example of the Lower Vistula River (Poland). Remote Sensing 2021, 13(23), 4775.

5. *Conrad, O.; Bechtel, B.; Bock, M.; Dietrich, H.; Fischer, E.; Gerlitz, L.; Wehberg, J.; Wichmann, V.; Böhner, J.* System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geosci. Model Dev. 2015, 8, 1991–2007.

6. *Galon, R.* Morfologia doliny i sandru Brdy. Stud. Soc. Scient. Tor. 1953, C, 1–6.

7. *Guerra, A.J.T.; Fullen, M.A.; Jorge, M.D.C.O.; Bezerra, J.F.R.; Shokr, M.S.* Slope processes, mass movement and soil erosion: A review. Pedosphere 2017, 27, 27–41.

8. *Heymann, Y.; Steenmans, C.; Croisille, G.; Bossard, M.* CORINE Land Cover. Technical Guide; Office for Official Publications of the European Communities: Luxembourg, 1994; p. 136.

9. *Hosmer, D.W.; Lemeshow, S.* Applied Logistic Regression, 3rd ed.; Wiley: New York, NY, USA, 2000; p. 528.

10. *Kornejady, A.; Ownegh, M.; Bahremand, A.* Landslide susceptibility assessment using maximum entropy model with two different data sampling methods. Catena 2017, 152, 144–162.

11. Map of the Polish Hydrographic Division; Department of Hydrography and Morphology of River Channels Institute of Meteorology and Water Management. 2007. Available online: http://mapa.kzgw.gov.pl/ (accessed on 10 December 2016).

12. *Marchi, L.; Fontana, G.D.* GIS morphometric indicators for the analysis of sediment dynamics in mountain basins. Environ. Geol. 2005, 48, 218–228.

13. *Melton, M.A.,* 1965. The Geomorphic and Paleoclimatic Significance of Alluvial Deposits in Southern Arizona. J. Geol. 73, 1–38.

14. *Merritt, W.; Letcher, R.; Jakeman, A.J.* A review of erosion and sediment transport models. Environ. Model. Softw. 2003, 18, 761–799.

15. *Moore, I.D.; Grayson, R.B.; Ladson, A.R.* Digital terrain modelling: A review of hydrogical, geomorphological, and biological applications. Hydrol. Process. 1991, 5, 3–30.

16. *Phillips, S.J.; Anderson, R.P.; Schapire, R.E*. Maximum entropy modeling of species geographic distributions. Ecol. Model. 2006, 190, 231–259.

17. *Phillips, S.J.; Dudik, M.* Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. Ecography 2008, 31, 161–175.

18. *Pournader, M.; Ahmadi, H.; Feiznia, S.; Karimi, H.; Peirovan, H.R.* Spatial prediction of soil erosion susceptibility: An evaluation of the maximum entropy model. Earth Sci. Inform. 2018, 11, 389–401.

19. *Planchon, O., Darboux, F.*, 2002. A fast, simple and versatile algorithm to fill the depressions of digital elevation models. Catena. 46, 159–176.

20. *Renard, K.G.; Foster, G.R.; Weesies, G.A.; McCool, D.K.; Yoder, D.C.* Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE); U.S. Department of Agriculture: Washington, DC, USA, 1997; Volume 703, p. 407.

21. *Saha, S.; Gayen, A.; Pourghasemi, H.R.; Tiefenbacher, J.P.* Identification of soil erosion-susceptible areas using fuzzy logic and analytical hierarchy process modeling in an agricultural watershed of Burdwan district, India. Environ. Earth Sci. 2019, 78, 649.

22. *Siriwardena, L.; Finlayson, B.L.; McMahon, T.A.* The impact of land use change on catchment hydrology in large catchment: The Comet River, Central Queensland, Australia. J. Hydrol. 2006, 326, 199–214.

23. *Solon, J.; Borzyszkowski, J.; Biedłasik, M.; Richling, A.; Badora, K.; Balon, J.; Brzezińska-Wójcik, T.; Chabudziński, Ł.; Dobrowolski, J.; Grzegorczyk, I.; Jodłowski, M.; Kistowski, M.; Kot, R.; Krąż, P.; Lechnio, J.; Macias, A.; Majchrowska, A.; Malinowska, E.; Migoń, P.; Myga-Piątek, U.; Nita, J.;*

Papińska, E.; Rodzik, J.; Strzyż, M.; Terpiłowski, S.; Ziaja, W. Psysico-geographical mesoregions of Poland: Veryfication and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica 2018, 91(2), 143-170.
24. *Sørensen, R.; Zinko, U.; Seibert, J.* On the calculation of the topographic wetness index: Evaluation of different methods based on field observations. Hydrol. Earth Syst. Sci. Discuss. Eur. Geosci. Union 2005, 2, 1807–1834.
25. *Szatten, D.* Wpływ zabudowy hydrotechnicznej na występowanie ekstremalnych stanów wody na przykładzie Brdy skanalizowanej. Inżynieria Ekol. 2016, 46, 55–60.
26. *Szatten, D.* Cascade-Dammed Rivers and Flood Phenomena - an Example of Inland Waterway in Bydgoszcz, Wasserwirtschaft 2022, 112(S1), 32-33.
27. *Szatten, D.; Habel, M.; Pellegrini, L.; Maerker, M.* Assessment of Siltation Processes of the Koronowski Reservoir in the Northern Polish Lowland Based on Bathymetry and Empirical Formulas. Water 2018, 10, 1681.
28. *Szatten, D.; Więcław, M.* Solar Climate Features Taking into Account the Morphometric Conditions of the Area and the Possibility of Using Them in Heliotherapy on the Example of the Cieplice and Kołobrzeg Health Resorts (Poland). Atmosphere 2021, 12, 383.
29. *Wischmeier, W.H.; Smith, D.D.* Predicting Rainfall Erosion Losses: A Guide to Conservation Planning. In Agriculture Handbook No. 537; USDA: Washington, DC, USA, 1978; p. 66. Available online: https://naldc.nal.usda.gov/download/CAT79706928/PDF (accessed on 7 November 2018).

Функціональні значення просторового аналізу в оцінці впливу грунтового покриву на прогнозування процесу ерозії

Сжаттен Д., Герман О., Тенговська Н.

Ерозія — це процес, що формує земну поверхню, відповідальний за надходження наносів до річкової системи. Виявлення зон, вразливих до ерозії, є критичним елементом управління наносами у водозбірному басейні, що дозволяє оцінити ступінь їх деградації. Дослідження ґрунтувалося на використанні просторових даних, цифрової моделі рельєфу (DTM) і Corine Land Cover (CLC) на прикладі двох водозбірних басейнів, розташованих на нижній течії річки Брда. Основною метою дослідження було оцінити вплив ґрунтового покриву на просторове прогнозування процесу ерозії в масштабі водозбору. Метод максимальної ентропії використовувався для визначення розподілу просторової ймовірності змінних навколишнього середовища, пов'язаних з процесом ерозії. Результати показали найбільшу прогностичну дію особливостей навколишнього середовища, пов'язаних з рельєфом, та з конкретними типами ґрунтового покриву. Прогностичні моделі можна успішно використовувати для прогнозування територій, потенційно схильних до ерозії.

Ключові слова: *ерозія; модель максимальної ентропії; передбачення, модель грунтового покриву (CLC); просторовий аналіз; водозбір річки Брда.*

Надійшла до редколегії 17.11.2022

DOI: https://doi.org/10.17721/2306-5680.2022.4.3
UDC 556.537

Bonheur M. N.[1*], Harmel O. O.[1], Christian T.[1, 2], Dieudonne M. N. G.[1], Bernard M.[1]
[1] Higher National Polytechnic School, Marien N Gouabi University, Brazzaville, Congo
[2] Higher Teacher's Training School, Marien Ngouabi University, Brazzaville, Congo

WATER EROSION POTENTIAL OF THE CONGO RIVER IN THE STANLEY-POOL BAY

In this paper, a scientific study on the understanding of the erosion and transfer processes of suspended solids or sediments from the Congo River into the Stanley-Pool Bay was conducted. For this purpose, a treatment of rainfall data over three decades (1990-2020), parameters influencing the process of erosive dynamics leading to the realization of the water erosion map using the Universal Soil Loss Equation (USLE), was done. Using open access spatial data and GIS, this USLE model allowed quantifying the rate of material transported over the three decades: a spatialization of erosion risks on the right bank of the Congo River, notably in the Stanley-Pool Bay, a topography dominated by steep slopes up to 10%, a high erosivity and erodibility and a low soil protection were revealed.

Finally, the results of the study show that about 40% of the study area is subject to soil loss. The erosion risk is very severe despite the vegetation cover.

***Key words**: Solid transport, sediments, modelling, models, Stanley Pool, Congo River.*

Introduction. The Congo River is the longest river in Africa (4,700 km) after the Nile, the second longest in the world after the Amazon in terms of flow (41,000 m^3s^{-1}) and has a basin area of 3.7 million km² at its mouth. It serves as a border in its upper part between the Republic