Investigating the Effect of Cross-Modeling in Landslide Susceptibility Mapping

Kamila Pawluszek-Filipiak *, Natalia Oreńczak † and Marta Pasternak †

Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, 50-375 Wroclaw, Poland; 111832@student.upwr.edu.pl (N.O.); 111837@student.upwr.edu.pl (M.P.)
* Correspondence: kamila.pawluszek-filipiak@upwr.edu.pl
† These authors contribute equally to this paper.

Received: 20 August 2020; Accepted: 7 September 2020; Published: 11 September 2020

Featured Application: Landslide Susceptibility Mapping using landslide inventory generated for the surrounding area can be generally carried out. However, the low reliability of such susceptibility map was observed in areas of critical geological structures. Thus, this should be borne in mind, when performing such a modeling in complex geological regions.

Abstract: To mitigate the negative effects of landslide occurrence, there is a need for effective landslide susceptibility mapping (LSM). The fundamental source for LSM is landslide inventory. Unfortunately, there are still areas where landslide inventories are not generated due to financial or reachability constraints. Considering this led to the following research question: can we model landslide susceptibility in an area for which landslide inventory is not available but where such is available for surrounding areas? To answer this question, we performed cross-modeling by using various strategies for landslide susceptibility. Namely, landslide susceptibility was cross-modeled by using two adjacent regions (“Łososina” and “Gródek”) separated by the Rożnów Lake and Dunajec River. Thus, 46% and 54% of the total detected landslides were used for the LSM in “Łososina” and “Gródek” model, respectively. Various topographical, geological, hydrological and environmental landslide-conditioning factors (LCFs) were created. These LCFs were generated on the basis of the Digital Elevation Model (DEM), Sentinel-2A data, a digitized geological and soil suitability map, precipitation, the road network and the Rożnów Lake shapefile. For LSM, we applied the Frequency Ratio (FR) and Landslide Susceptibility Index (LSI) methods. Five zones showing various landslide susceptibilities were generated via Natural Jenks. The Seed Cell Area Index (SCAI) and Relative Landslide Density Index were used for model validation. Even when the SCAI indicated extremely high values for “very low” susceptibility classes and very small values for “very high” susceptibility classes in the training and validation areas, the accuracy of the LSM in the validation areas was significantly lower. In the “Łososina” model, 90% and 57% of the landslides fell into the “high” and “very high” susceptibility zones in the training and validation areas, respectively. In the “Gródek” model, 86% and 46% of the landslides fell into the “high” and “very high” susceptibility zones in the training and validation areas, respectively. Moreover, the comparison between these two models was performed. Discrepancies between these two models exist in the areas of critical geological structures (thrust and fault proximity), and the reliability for such susceptibility zones can be low (2–3 susceptibility zone difference). However, such areas cover only 11% of the analyzed area; thus, we can conclude that in remaining regions (89%), LSM generated by the inventory for the surrounding area can be useful. Therefore, the low reliability of such a map in areas of critical geological structures should be borne in mind.

Keywords: landslide; landslide susceptibility modeling; landslide controlling factors; landslide inventory
1. Introduction

A landslide is the movement of earthen materials down a slope under the influence of gravity [1] and occurs when earthen material exceeds the shear strength (resistance to shearing) [2]. Landslide events can cause damage to buildings, infrastructure and property and endanger human life [3–5]. According to [6], landslides are in seventh place when it comes to the destruction of human life and property. It is estimated that the frequency of landslides is increasing. The main reasons for the larger landslide vulnerability are (1) climate change and more extreme weather conditions; (2) the overexploitation of natural resources and deforestation, (3) growing urbanization and unrestrained land use, (4) the increased use of traditionally non-populated mountainous regions for recreational and transportation purposes, pushing the borders further into hazardous terrain [6].

In Poland, the area most susceptible to landslides is the Carpathians. The reason for this is the nature of the relief and the geological structure. The high slopes combined with the flysch conditions render the Carpathians a region strongly prone to landslide occurrence. About 6% of the country is covered by the Carpathians, where 95% of all the landslides in Poland have been registered. In 2010, 50,000–60,000 landslides were recorded in the Carpathians, an average of one landslide per km² [7]. Landslide areas cover about 30–40% of the province areas in this region. The activation of numerous landslides in 2000 and 2010 by intense precipitation had disastrous consequences. Many residential buildings and road sections were destroyed [8]. There have been many cases of economic losses, which are estimated in millions of Polish zlotys. Some landslides are activated almost every year, which results in the destruction of residential and commercial buildings, transport infrastructure, transmission routes and agricultural and forest areas [9]. In agricultural areas, soil mixed with the layer located below presents inferior properties for agricultural production. The restoration of soil fertility in such areas is a long-term process [7]. Therefore, to mitigate the negative effects of landslides, it is necessary to effectively estimate landslide susceptibility and hazards [10,11].

From a mathematical perspective, landslide susceptibility mapping (LSM) presents the probability of landslide occurrence in a specific area based on an analysis of the terrain conditions and environmental conditions calculated from geo-environmental analysis. This describes the degree of proneness of specific terrain to landslides [12]. LSM is necessary for hazard assessment and the effective planning and management of regional sustainable development [13]. It is the subject of various studies worldwide [2,3,13–17]. The factors used for assessing landslide susceptibility are usually called Landslide Controlling Factors (LCFs). These factors are analyzed to create predictive models for landslide susceptibility, and they usually include topographical, geological, hydrological and environmental conditions. Effective LSM provides various land-use planners and decision makers with an opportunity to determine the regions appropriate for urban expansion and allows them to make the best possible use of land while avoiding landslide-prone areas [13,18].

Researchers all over the world have applied various methods for LSM. These methods can be qualitative or quantitative [14]. Qualitative methods are subjective and determine susceptibility heuristically, while quantitative methods involve the calculation of numerical measures, i.e., the likelihood of the occurrence of landslide phenomena in any susceptibility zone [12]. Among these quantitative approaches, the analytic hierarchy process (AHP) [14], the frequency ratio (FR) [14,19,20], the statistical index (SI) [20], the evidential belief function (EBF) [21], Dempster–Shafer (DS) analysis [22], logistic regression (LR) [19], the weights of evidence (WOE) model [20,21] and fuzzy logic (FL) [23] exist. Machine learning (ML) approaches have also been applied for LSM in the last few decades. Among them, the Support Vector Machine (SVM) [24,25], Artificial Neural Network (ANN) [19,21,23] and Random Forest (RF) [26] are increasingly used. The fundamental source for LSM with any of abovementioned methods is the landslide inventory map, which presents the location and extent of landslides.

Generally, when modeling terrain’s susceptibility to land sliding, 70% of existing landslides are used for modeling and 30% are used for model validation [2,3,13,18,20–22,24,27], but some authors have even applied 80% of existing landslides for modeling purposes [19,28]. The landslides for modeling
are selected randomly across the entire study area, so they can capture a variety of conditions. This is a huge advantage in LSM. Unfortunately, there are still areas for which landslide inventory maps are simply not generated due to financial or reachability issues; they are not available in some hardly accessible areas. The authors of [29] presented a summary of the completeness of landslide inventories for various countries in Europe in 2012, which confirms that there are still areas for which landslide maps have not been generated. For example, landslide inventory in Poland has been generated step by step (commune area after commune area), and the generation of such an inventory sometimes proved to be very time consuming when the geological conditions were complex, resulting in a lack of landslide inventory in such regions. From another point of view in such a region, there is still the need for land-use planning, decision making, and the continuation of building and investment.

Considering this led to the following research question: could we assess landslide susceptibility in an area for which landslide inventory is not available but where it is available for the surrounding places? To answer this research question, we performed LSM based on so-called cross-modeling. More specifically, we divided our study area into two separate regions (“Łososina” and “Gródek”) and performed modeling for the entire study area based on the “Łososina” and “Gródek” areas in the first and the second modeling scenarios, respectively. For the LSM, we utilized various topographical, geological and environmental LCFs together with the widely used Frequency Ratio method. LSM was performed in the study area greatly affected by landslide activity in the Polish Carpathians, in the area of the Roźnów Lake.

2. Materials and Methods

2.1. Study Area

The study area is located in the Outer Carpathians in the Małopolskie voivodeship. The main river of Dunajec is located in the study area, and Roźnów Lake was created as result of damming the Dunajec River. This dam is used in the Roźnów Power Plant [30]. The Roźnów water reservoir is one of the main elements for managing the water resources of the Dunajec river basin. (Figure 1). The study area covers from 49°40′ N to 49°46′ N latitude and from 20°38′ E to 20°48′ E longitude, which corresponds to 136 km² (Figure 1). Around 18.2 km² of this area is affected by landslides. According to Varnes’ classification, updated by Hungr et al. [31], all landslides have a slide type of movement. According to Hungr’s classification [31], within the Łososina commune, there are rock rotational slides (no. 6), clay/silt rotational/planar and compound slides (no. 11, 12, 14). Unfortunately, the landslide inventory provided by Polish National Geological Institute does not represent more detailed characteristic of landslide types e.g., shallow/deep-seated landslides or planar/rotational slides. Generally, landslides are classified as deep or shallow based on the material, movement mechanism and depth of the rapture surface [32]. The authors of [33,34] reported that landslide is considered as shallow when the depth of the sliding plane is less than 10 m and deep seated when sliding plane is deeper than 10 m. When investigating sizes [35,36], characteristics and slip depth of some landslides described in the landslide inventory documentation [37,38], we can concluded that shallow as well as deep seated landslide exists in investigated region. Generally in this region, landslides are slow- to very-slow-moving. The study area mainly consists of Eocene–Oligocene sandstones and shales and Upper Cretaceous sandstone and conglomerate–Lower Stebna layers. This is one of the most landslide-affected areas in Poland. Additionally, due to the complex geological conditions, landslide inventories in this region of the eastern shore of Roźnów Lake were unavailable for a long time. Thus, its situation suited the research question of this paper.
2.2. Methodology

The methodology flowchart is presented in Figure 2. The study area was divided into two regions called “Łososina” and “Gródek”, separated by Dunajec River (also the boundary of the Łososina and Gródek communes). These regions were used for cross-modeling. This means that in the first model, “Łososina” was used for modeling, while in the second, “Gródek” was used for the modeling of the landslide susceptibility of the entire study area. The official national landslide inventory map (SOPO) was used for LSM. The Frequency Ratio (FR) method was applied as a tool for landslide modeling. The susceptibility assessment was performed in the same manner by using various landslide input data. Based on this, a direct comparison between these two strategies was possible. More detailed descriptions of data and methods used are presented in the following subsections.
2.3. Input Data

The landslide inventory database (SOPO) from the Polish National Geological Institute was used for the input data (Figure 1). These data allowed the generation of models and validation datasets. The existing landslide locations and boundaries within the SOPO database were captured using conventional techniques, mostly comprising field reconnaissance, the visual interpretation of aerial photographs, and the analysis of historical data [39]. The landslides within the study area are stored in the SOPO database and were mapped during field work in the years 2010, 2011, 2012, 2013, 2014 and 2015 [35,37,38,40]. Additional mapping was also performed on the basis of topographic maps at a 1:10 000 scale, supported by stereoscopic analyses of aerial photographs and LiDAR data [9].

Various Landslide Conditioning Factors (LCFs) were generated from the data captured from different sources. Table 1 presents the data sources used to create so-called second-order input data such as the Digital Elevation Model (DEM), geological and soil map etc. The LiDAR data were acquired within the framework of the IT System of the Country Protection (ISOK) project. Almost the entire area of Poland has been scanned for the implementation phase of the extraordinary hazard (mostly water hazard) protection system (ISOK project) [41]. A point cloud with a density of 4–6 points/m² was generated, and the calculated Root Mean Square Error was about 0.15 m for the height coordinate [41]. This LiDAR point cloud was subsequently used for DEM generation. To decrease the data volume and discard some of the artefacts from the original DEM, we followed the recommendations of [42–44] and generated a DEM with a resolution of 2 m. This approach appears to be common among various papers, and many authors have reported that the finest DEM resolution is not always the best choice [42–44]. Based on the DEM, topographical LCFs were subsequently generated as described in Section 2.4.

A Sentinel-2A image acquired via the Copernicus Scientific data hub was used to extract the boundary of Roźnów Lake. This shape was extracted by the calculation of the Normalized Difference Vegetation Index (NDVI). More specifically, an NDVI value lower than 0 was used to extract the shape of the lake, based on which another LCF was calculated (the lake proximity). Moreover, an agricultural soil map acquired from the geoportal of the Małopolskie voivodeship was used to generate a soil-suitability map. A geological map was also obtained from the Polish National Geological Institute.
As well as the geological map, the soil maps were digitized and stored as vector layers in ArcGIS (version 10.6, ESRI, Redlands, CA, USA). Additionally, a thrust and fault network was generated based on previous work [30] via a digitization process. The road network was acquired from OpenStreetMap (OSM). Because the river network in OSM is very sparse, the stream network was extracted with the DEM, with which the flow accumulation and direction were initially calculated. The subsequent thresholding of the flow accumulation values allowed the extraction of the stream network. Finally, this network was manually refined and converted into the vector layers. Because precipitation is a direct trigger of landslides worldwide, we downloaded the precipitation measurements from four different meteorological stations in this area. We utilized measurements from 2019 due to the changes of the weather conditions caused by the climate change. From one year to another, we observed much more extreme weather phenomenon. Thus, to represent the most real and current rainfall situation, we applied the rainfall measurement from 2019. A precipitation map was generated based on these measurements by inverse distance weighted interpolation. A summary of all the data used in this study is presented in Table 1.

| Generated Second-Order Input Data | Method | Data Type | Data Source | Link |
|----------------------------------|--------|-----------|-------------|------|
| DEM                              | Ground point extraction (class = 2) | LiDAR | ISOK | http://isok.gov.pl/hydroportal.html |
| Stream network                    | Flow direction and flow accumulation analysis | Shapefile | DEM | --- |
| Geology map                       | Digitalization | Raster | Polish National Geological Institute, | https://geolog.pgi.gov.pl/ |
| Roźnów lake shapefile             | NDVI < 0 | Sentinel-2A satellite image (25 March 2020) | European Space Agency | https://scihub.copernicus.eu/ |
| Land cover map                    | Maximum Likelihood Classification | Sentinel-2A satellite image (25 March 2020) | European Space Agency | https://scihub.copernicus.eu/ |
| Road network                      | - | Shapefile | OpenStreetMap | https://download.geofabrik.de/ |
| Soil Suitability Map              | Digitalization | Raster | Małopolska Spatial Information infrastructure | https://miip.geomalopolska.pl/ |
| Fault and thrust network          | Digitalization | Raster | [30] | [30] |
| Precipitation                     | Inverse distance weighted interpolation | Precipitation measurement in meteorological stations (points) | Institute of Meteorology and Water Management | https://danepubliczne.imgw.pl/ |

### 2.4. Preparation of Landslide Conditioning Factors

From the DEM generated from LiDAR data, various topographical layers were generated (LCFs). Table 2 presents an overview of various widely applied LCFs generated from the DEM and Figure 3 presents a graphical representation of some of the used LCFs. Based on some DEM analysis, hydrology-related layers were also extracted: the compound topographic index (CTI), integrated moisture index (IMI) and flow direction (FD). To create accurate LSM, we also generated a stream proximity layer based on the stream network extracted from the DEM (see Section 2.3) and Euclidian Distance Buffering (EDB) tool within ArcGIS.

The additional auxiliary data presented in the previous subsection and Table 1 made the generation of additional geological, hydrological and environmental factors possible. Among them, tectonics, lithostratigraphy and faults and thrust proximity were possible to generate by utilizing the geology map and [30]. The Normalized Difference Vegetation Index (NDVI) and lake proximity layers were created from the Senitel-2A data acquired on 25 March 2020. The lake proximity was generated based on Euclidian distance buffering and the lake shapefile extracted from the NDVI (Section 2.3). The Sentinel-2A data were also used to create a Land Cover (LC) map by supervised classification using the Maximum Likelihood (ML) approach and the Sentinel-2A spectral bands. The Overall Accuracy
(OA) of this LC map was assessed by comparing ground truth samples with the classification results, indicating that the OA of our map was approximately 94%—sufficient for this study. The shapefile of the road network was captured from OpenStreetMap, and similarly to previous distance-related layers, the distance to road layer was created. The soil suitability layer, which presented complexes of agricultural soil suitability, was created based on the digitalization of the soil suitability map.

Table 2. Landslide conditioning factors used in presented study (ML: Machine learning).

| Variable                  | Data Used          | Technique | Classification Method | References                      |
|---------------------------|--------------------|-----------|-----------------------|---------------------------------|
| elevation                 | DEM                | —         | Natural Jenks          | [2,3,13–15,19,22,26,46]         |
| aspect                    | DEM                | ArcGIS    | Natural Jenks          | [13,14,21,22,24,26]             |
| slope                     | DEM                | ArcGIS    | Natural Jenks          | [2,3,13–16,19–22,24]            |
| curvature                 | DEM                | ArcGIS    | Natural Jenks          | [3,13,16,18,20,21,24]           |
| side exposure index (SEI) | DEM                | [47]      | Natural Jenks          | [45]                            |
| tectonics                 | geology map        | —         | —                     | [3,13,14,19,20,22,24,26]        |
| lithostratigraphic unit   | geology map        | —         | —                     | [3,13,14,19,20,22,24,26]        |
| fault proximity           | geology map        | EDB       | Natural Jenks          | [13,19–22,24,26]                |
| thrust proximity          | geology map        | EDB       | Natural Jenks          | [49,50]                         |
| distance to streams       | DEM                | EDB       | Natural Jenks          | [3,13,19,20]                    |
| distance to lake          | Roznow lake shapefile | EDB     | Natural Jenks          | [16,24]                         |
| compound topographic index (CTI) | DEM | Natural Jenks | [13,48,51,52] |
| integrated moisture index (IMI) | DEM | [47] | Natural Jenks | [46,53] |
| flow direction            | DEM                | [47]      | Natural Jenks          | [45,54]                         |
| precipitation             | measurements from meteorological stations | — | Natural Jenks | [13,51,55] |
| distance to roads         | road network       | EDB       | Natural Jenks          | [3,13,14,16,19,22,24,28,51]    |
| Land Cover (LC)           | Sentinel-2A        | Supervised ML classification | — | [2,3,13,28,51] |
| NDVI                      | Sentinel-2A        | NIR−RED in NIR and RED are inferred | Natural Jenks | [3,13,24,28,51] |
| soil suitability          | digitized soil map | —         | —                     | [3,13,21,24,28,51]             |

2.5. Landslide Susceptibility Modeling

To fully achieve the goal of this study, we used various data for landslide susceptibility assessment. Namely, we generated the two landslide susceptibility models based on landslides located within the “Łososina” and “Gródek” regions in the first and second modeling scenarios, respectively. The qualitative information about the number of landslides used for modeling and its contribution in the total analyzed area is presented in Table 3. A graphical representation of the region separation is presented in Figure 4. Based on this, it can be observed that 46% and 54% of the total detected landslides were used for the LSM in “Łososina” and “Gródek” strategies, respectively. Moreover, it is apparent that there is an 8% difference in the landslides used for modeling between these two strategies. At this point, it is worth reiterating that 70% of the landslides are typically used for LSM in the literature [2,3,13,18,20–22,24,27]. Moreover, a random sampling strategy is used for assessing landslide susceptibility; the landslides used for modeling are distributed randomly and evenly across the investigated area, so the variety of conditions (LCFs) can be better captured. Considering this, in the first and second strategies, we used fewer landslides for modeling purposes. Thus, we supposed that this modeling of landslide susceptibility would have lower performance than that usually presented in the literature. However, the goal of the presented work was to investigate whether landslide inventory could be used for LSM in surrounding regions rather than to strive for accuracy.
2.5. Landslide Susceptibility Modeling

To fully achieve the goal of this study, we used various data for landslide susceptibility assessment. Namely, we generated the two landslide susceptibility models based on landslides located within the "Łososina" and "Gródek" regions in the first and second modeling scenarios, respectively. The qualitative information about the number of landslides used for modeling and its contribution in the total analyzed area is presented in Table 3. A graphical representation of the region separation is presented in Figure 4. Based on this, it can be observed that 46% and 54% of the total detected landslides were used for the LSM in "Łososina" and "Gródek" strategies, respectively.

Moreover, it is apparent that there is an 8% difference in the landslides used for modeling between these two strategies. At this point, it is worth reiterating that 70% of the landslides are typically used for LSM in the literature [2,3,13,18,20–22,24,27]. Moreover, a random sampling strategy is used for assessing landslide susceptibility; the landslides used for modeling are distributed randomly and evenly across the investigated area, so the variety of conditions (LCFs) can be better captured. Considering this, in the first and second strategies, we used fewer landslides for modeling purposes. Thus, we supposed that this modeling of landslide susceptibility would have lower performance than that usually presented in the literature. However, the goal of the presented work was to investigate whether landslide inventory could be used for LSM in surrounding regions rather than to strive for accuracy.

Figure 3. Examples of landslide conditioning factors utilized in this study (a) aspect, (b) fault proximity, (c) land cover, (d) CTI, (e) flow direction, (f) lake proximity, (g) tectonics, (h) precipitation, (i) NDVI, (j) road proximity, (k) SEI, (l) slope, (m) stream proximity, (n) thrust proximity, (o) elevation, (p) lithostratigraphic units, (r) soil suitability.
Table 3. Landslides used for landslide susceptibility modeling in various strategies.

| Strategy       | Map     | Study Area | No of Landslide in Total Study Area | Landslide Area in Total Study [km²] | Percentage of Total [%] |
|----------------|---------|------------|-------------------------------------|-------------------------------------|------------------------|
| 1st strategy   | SOPO    | Łososina   | 322                                 | 8.31                                | 46                     |
| 2nd strategy   | SOPO    | Gródek    | 425                                 | 9.94                                | 54                     |
| Total study area |        |            | 747                                 | 18.25                               | —                      |

Figure 4. Study area division into “Łososina” region and “Gródek” region superimposed on lithostratigraphic units.

2.6. Application of Frequency Ratio Model for Landslide Susceptibility Zonation

The Frequency Ratio (FR) is a geospatial assessment tool used to estimate the susceptibility to landslides in a given research area [13]. It belongs to the bivariate statistical methods, and its value depends on the relationship between the location of landslides and LCFs [27]. For LCFs, weights are assigned based on the ratio of the number of observed landslides to the area of the study area. The weights, represented as FRs, can be calculated using landslide inventory and each specific LCF [27]. When $j$ is the class of a specific LCF ($i$), the FR is defined by the following equation:

$$S_{CAI_i} = \left( \frac{E_i}{F_j} \right)$$

(1)

where:

- $A$ = the number of pixels of the landslide in each LCF class
- $B$ = the total number of pixels of the landslide in the test area
- $C$ = the number of pixels in each LCF sub-class
- $D$ = the total number of pixels in the test area [1]

Accordingly, the FR was calculated by overlaying landslide pixels with the thematic layers or LCF layers presented in Section 2.4. Values obtained using this method greater than 1 imply high landslide susceptibility within this class [13] and a strong correlation between the landslide occurrence and LCF class [28]. Values below 1 indicate no or a slight correlation between the LCF and landslide occurrence [13,28].
The Landslide Susceptibility Index (LSI) was subsequently calculated for each pixel in the image \((x,y)\) according to the formula:

\[
\text{LSI}_{xy} = \sum_{i=1}^{n} FR_{i,j}
\]  

(2)

Based on natural breaks, Jenks [56] developed an optimization method to minimize within-class variance while maximizing between-class variance. This classification method is generally implemented into GIS software, such as ESRI@ ArcGIS software or QGIS (free open source software). The classes are split according to natural clusters inherent in the data, and the boundaries are statistically determined when relatively large jumps occur within the susceptibility indices as determined by their variance. The LSI values were separated based on this method into five susceptible classes. This number of susceptibility zones is commonly used in small-scale landslide susceptibility mapping [57,58]: very low, low, moderate, high and very high. These are considered adequate for revealing any spatial patterns preserved in a dataset and aiding the interpretation of these LSMs [59].

2.7. Methods for Model Validation

Model validation is a crucial step that indicates whether the generated model achieves a certain level of accuracy. Without accuracy assessment, generated models are meaningless [13]. We applied the Seed Cell Area Index (SCAI) and Relative Landslide Density Index \((R_{\text{ind}})\) to evaluate our landslide susceptibility maps in this study. We also calculated a residual map and correlation index between two susceptible maps. The SCAI and \(R_{\text{ind}}\) were calculated for validation and modeling areas for both models.

2.7.1. Index of Relative Landslide Density

Bearing in mind that the LSM value was used to distinguish susceptible and non-susceptible areas, landslides may be expected to occur in areas with more susceptible zones [60]. A relative landslide density index \((R_{\text{ind}})\) was calculated to verify this. This index is defined by the ratio of the landslide area and given susceptibility class to the overall landslide density. The index takes the following form:

\[
R_{\text{ind}} = 100 \cdot \frac{n_i/N_i}{\sum n_i/N_i}
\]

(3)

where:

- \(n_i\) = the number of landslides observed in a susceptibility class
- \(N_i\) = the area covered by the cells of this class [61].

2.7.2. Seed Cell Area Index

The Seed Cell Area Index (SCAI) validation technique used in this study was developed by Süzen and Doyuran [62]. It is described as the ratio between the percentage of pixels of the exact class of landslide susceptibility and the percentage of the pixels of existing landslides in a given landslide susceptibility zone. The SCAI is assumed to be a reliable validation technique [13,14]. If its values decrease from very low to very high classes of LS, the model is regarded as excellent [13]. When \(i\) is the specific susceptibility map, SCAI is represented as follows:

\[
\text{SCAI}_i = \left( \frac{E_i}{F_i} \right)
\]

(4)

where: \(E_i\) = percentage of landslide pixels in specific susceptibility class to total landslide pixels \(F_i\) = percentage of pixels in specific susceptibility class to total image pixels.
2.7.3. Map/Model Comparison

To evaluate the reliability of the two susceptibility maps generated based on two different landslide input datasets, we performed model or map comparison. Firstly, we determined the raster difference between these two maps, showing how these two maps differed from each other. By comparing two models with different susceptibility zones, a so-called residual map was generated [63]. This residual image showed how pixels shifted from one landslide susceptibility class to another between these two maps. Thus, a residual image can have a maximum five different classes: no difference, one-zone difference (1, −1), two-zone difference (2, −2), three-zone difference (3, −3) and four-zone difference (4, −4) [14]. We also calculated the Pearson correlation coefficient between these two landslide susceptibility maps to evaluate their similarity.

3. Results

This section comprises the following three subsections: (1) the spatial relationship between landslide and conditioning factors, and the FR indexes used for the LSI calculations (presented in Appendices A and B); (2) a presentation of the landslide susceptible maps generated by two models; and (3) the validation and comparison of the generated models using the SCAI, $R_{ind}$ and model comparison.

3.1. The Spatial Relationship Between Landslide Locations and Analyzed Landslide-Controlling Factors

The frequency ratios for the first and second models are presented in Appendices A and B, respectively. Observing the FRs, it is apparent that the topographic factors were not of great importance for the preparation of the LSM in this study. To the contrary, it can be observed that the lithostratigraphic units were more important than tectonics or other geological or environmental conditioning factors. For clarity, the ten highest frequency ratios achieved for each model are shown in Figure 5, from which it is clear that the lithostratigraphic units were the most important variable in both models. Soil suitability also played an important role in landslide occurrence. In the “Łososina” model, precipitation and tectonic were also important landslide-controlling factors.

![Figure 5. Importance of landslide conditioning factors in landslide susceptibility mapping (LSM) based on (a) “Łososina” and (b) “Gródek”.](image)

3.2. Landslide Susceptibility Maps

The LSIs were calculated as described in Section 2.5 based on the FRs presented in Appendices A and B and afterwards sorted into five susceptibility classes by Natural Jenks classification. Figure 6a,b present various LSIs calculated for the model based on “Łososina” and based on “Gródek”, respectively. Similarly, Figure 6c,d present the susceptibility classes (SC) for the model based on “Łososina” and that based on “Gródek”, respectively.
Figure 6. Landslide Susceptible Index (LSI) and landslide susceptibility zones for the (a,c) “Łososina”-based model and (b,d) “Gródek”-based model.

The results from the “Łososina” model show that the very low, low, moderate, high and very high landslide susceptibility zones of the LSM cover 5%, 10%, 28%, 31% and 26% of the investigated study area, respectively (Figure 7a). The “Gródek” model results show that the very low, low, moderate, high and very high landslide susceptibility zones of the LSM cover 7%, 20%, 35%, 28% and 10% of the investigated study area, respectively (Figure 7b). From these indices, the same quantity can be observed for very high and high susceptible classes. Some relatively high differences can be observed within the low susceptibility class.
3.3. Evaluation of Landslide Susceptibility Models

3.3.1. Seed Cell Area Index

We evaluated the achieved susceptibility models based on the SCAI index; however, our evaluation was performed for split areas (“Łososina” and “Gródek”). This allowed for the better investigation of possible changes (the modeling and validation splitting strategy are described in Section 2.5). If the values of the SCAI decrease from very low to very high classes of LS, the model is regarded as excellent [13]. Table 4 presents percentage of each susceptible class, landslide observed in this specific class and SCAI index for both models. We can observe that based on the evaluation of the LSM in the modeling area, the SCAI index was extremely high (2491) and extremely low (0.42) for the “very low” and “very high” susceptible zones, respectively. These are exceptionally good results. A somewhat lower performance can be observed for the LSM based on “Gródek” and evaluated in the “Gródek” area; however, even its results were largely correct. Moreover, based on the evaluation of our results in the validation area, the SCAI index for the “very low” class in both cases (“Łososina” and “Gródek” model) was higher than 50, and it was below 0.5 for the “very high” susceptibility class, which is also considered appropriate.

Table 4. Landslide susceptibility model evaluation based on modeling and validation study areas.

| Model/Modeling Area | Class | Validation Area | Pixels in Domain | % | Landslide Pixels within the Specific Class [km²] | Percentage of Total [%] | SCAI |
|---------------------|-------|----------------|-----------------|---|---------------------------------|------------------------|-----|
| Łososina            | Very low | Low | 630,917 | 0.06 | 46 | 0 | 2491.70 |
|                     |        | Moderate | 2,064,901 | 0.18 | 11,417 | 0.01 | 32.86 |
|                     |        | High | 2,900,312 | 0.25 | 213,545 | 0.10 | 2.47 |
|                     |        | Very High | 3,515,091 | 0.31 | 841,964 | 0.41 | 0.76 |
|                     | Very low | Lososina | 2,323,889 | 0.20 | 1,010,439 | 0.49 | 0.42 |
|                     |        | Very low | 877,306 | 0.04 | 1645 | 0 | 66.82 |
|                     |        | Low | 6,874,753 | 0.35 | 144,129 | 0.06 | 5.98 |
|                     |        | Moderate | 6,843,835 | 0.34 | 907,641 | 0.37 | 0.94 |
|                     |        | High | 4,534,307 | 0.23 | 1,173,528 | 0.47 | 0.48 |
|                     | Very High | Gródek | 713,775 | 0.04 | 259,295 | 0.10 | 0.34 |
Table 4. Cont.

| Model/Modeling Area | Class   | Validation Area | Pixels in Domain | Landslide Pixels within the Specific Class [km²] | Percentage of Total [%] | SCAI |
|----------------------|---------|-----------------|------------------|-----------------------------------------------|-------------------------|------|
| Gródek               | Very low|                 | 894,142          | 1006                                          | 0.08                    | 194.50 |
|                      | Low     |                 | 3,390,427        | 22,136                                        | 0.01                    | 33.48  |
|                      | Moderate|                 | 6,373,115        | 324,619                                       | 0.13                    | 4.27   |
|                      | High    |                 | 6,344,671        | 953,086                                       | 0.38                    | 1.45   |
|                      | Very High|                | 2,841,621        | 1,185,391                                     | 0.48                    | 0.52   |
| Lososina             | Very low|                 | 1,236,346        | 3176                                          | 0.11                    | 70.74  |
|                      | Low     |                 | 2,948,451        | 196,954                                       | 0.09                    | 2.72   |
|                      | Moderate|                 | 4,448,486        | 924,964                                       | 0.45                    | 0.87   |
|                      | High    |                 | 2,431,304        | 786,222                                       | 0.38                    | 0.56   |
|                      | Very High|               | 370,523          | 166,095                                       | 0.08                    | 0.41   |

3.3.2. Index of Relative Landslide Density

The values of relative landslide density index $R_{ind}$ calculated for high and very high susceptibility classes are presented in Table 5. It can be observed that the $R_{ind}$ calculated for the area used for modeling is very high for both models (90% and 86%). For the validation areas, located on the other side of the river, the $R_{ind}$ are significantly lower (57% and 46%). This indicates changes in accuracy according to landslide susceptibility. Therefore, for the better investigation of the model performance, $R_{ind}$ should also be taken into account beside the SCAI index.

Table 5. $R_{ind}$ calculated for very high and high susceptibility classes.

| Area               | “Lososina” [%] | “Gródek” [%] |
|--------------------|----------------|--------------|
| “Lososina” area    | 90             | 46           |
| “Gródek” area      | 57             | 86           |
| Total              | 72             | 68           |

3.3.3. Map/Model Comparison

To better investigate the similarity of the models, we calculated the LSI and susceptible zone difference between them (Figure 8). The residual maps present the differences in the susceptibility zones. Five differences in the susceptibility classes can be distinguished (0–4 zones difference), as presented in Table 6. Green color represents no difference in the susceptible zones between these two models, while light red and light blue represent one susceptible zone difference (1, −1). According to Table 6 almost half of the map (47%) presents no difference in landslide susceptibility zones, and 42% differs in one susceptibility zone. Based on the difference between the left and right images, it can be seen that negative and positive values exist between these two sides of the study area, respectively (Figure 8). This is because the “Lososina” model was adjusted to the “Lososina” area and the “Gródek” model was adjusted to the “Gródek” area.
validation area shows that 46% and 57% of landslides fall into the high and very high susceptibility zones in the “Łososina” and “Gródek” models. This indicates that another classification method should be considered to effectively differentiate the susceptibility zones (e.g., quantiles, IsoData). This issue has been discussed in [60].

The correlation index calculated for both susceptible maps is 0.697. This value is quite similar to the total average landslide density in the high and very high susceptibility zones for the entire study area (compare with Table 5). Therefore, the overall accuracy of both of these susceptibility maps for the entire investigated region can be estimated at 70%. However, it must be mentioned that the accuracy changes from region to region. In the area where the landslides used for modeling are located, 90% accuracy can be expected, while in the area where the landslides used for modeling are not preserved (validation area), an LSM accuracy between 46% and 57% can be expected.

4. Discussion

Based on a comparison of the SCAI indices, the general performance (in terms of accuracy) of both models can be described as good. For the validation study area, the SCAI index was higher than 50 and lower than 0.5 for the very low and very high susceptibility classes, respectively. This shows higher performance than that described in other studies [13,14,55]. The $R_{ind}$ calculated for the validation area shows that 46% and 57% of landslides fall into the high and very high susceptibility zones in the “Gródek” and “Łososina” models, respectively. This implies that besides the SCAI index, the $R_{ind}$ should also be used to evaluate the LSM. The explanation for the low value of $R_{ind}$ for the high and very high classes is that 37% and 45% of the landslides are located in the moderate class in the “Łososina” and “Gródek” models. This indicates that another classification method should be...
considered to effectively differentiate the susceptibility zones (e.g., quantiles, IsoData). This issue has been discussed in [60].

When comparing these two models, the SCAI indexes for Lososina model are more satisfactory. This is mostly due to the high SCAI values for very low and low susceptible zones and very low values for high and very high susceptible zones. Moreover, relative landslide density \( (R_{\text{ind}}) \) is higher for Lososina model (72\%). Therefore, this model is more reliable than the Gródek model \( (R_{\text{ind}} = 68\%) \). This is surprising because it was expected that the “Gródek” model would better predict landslide susceptibility due to the greater amount of landslide used for modeling (54\%) when compared with “Lososina” model (46\%). Nevertheless, this indicate that the greater amount of landslides used for modeling does not go hand in hand with improved landslide susceptibility assessment.

As we mentioned in the Introduction section, scientists applied a randomly selected 70\% of the landslides for modeling and 30\% for validation. In the selection strategy, the landslides used for the modeling are distributed across the study area. Instead of our sampling strategy (splitting the area for the modeling and validation regions), landslides distributed evenly across the image can better “capture” a variety of topographical, geological and other environmental conditions (LCFs). When the study area is split into modeling and validation areas, it is possible for some landslide-prone geological units to be absent from the area used for modeling. Additionally, by comparing Figure 8 with LCFs, it can be observed that differences of up to two or three susceptible zones occur in the areas of faults and thrust proximity (intensive red and blue color). These differences of two classes can also be observed in changes of lithostratigraphic units (intensive red and blue color). This additionally confirmed our notion that the landslide sampling strategy had a crucial effect on the accuracy of LSM.

To better investigate the difference between these two models, a correlation matrix between the difference in the LSI index (Figure 8a) and each LCF was calculated and is presented in Figure 9. Based on this, it can be concluded that this difference between the models highly corresponds to the fault, lake, and thrust proximity. It can therefore be deduced that the landslides used for modeling did not capture the variability of geological (thrust and fault proximity) and environmental (lake proximity) conditions. Landslides that are better distributed across the entire study area can better describe the variety of geological and environmental conditions (e.g., thrust, fault and lake proximity) and therefore better predict landslide susceptibility.

![Figure 9. Correlation index between raster representing LSI difference between two susceptible models and each landslide-conditioning factor (LCF) (LC: Land Cover, IMI: Integrated Moisture Index, SEI: Side Exposure Index, CTI: Compound Topographic Index, TPI: Topographic Position Index).](image-url)

This outcome answers our research question whether we can perform LSM in an area for which a landslide inventory is not available but where such an inventory is available for the surrounding region. Based on this study, we can infer that the assessment of landslide susceptibility based on surrounding landslide inventories cannot be effectively performed in the areas when the geological and environmental conditions have changed. Generally, based on the results in Table 6, there is a 47\%
chance of being correct with the susceptibility zone and a 42% chance of error with one susceptibility zone. Therefore, we can generally perform landslide susceptibility modeling based on the landslide inventory for a neighboring region. However, it should be reiterated that there is 10% chance of our susceptibility map differing from target landslide susceptibility of two zones in some areas. These are generally located in areas with significant changes in the geological or environmental conditions. In this case, when we considered only very low susceptible classes for the decision making, this susceptibility map can be used for decision making and planning.

Another aspect which should be discussed here is the variability of landslide type used for LSM. Since the information about the specific landslide type (shallow/deep seated or planar/rotational) is not available within the national inventory, all landslides were used for LSM. A lack of differentiation between landslide types used for LSM is practiced by many researchers [3,13,14,22,55,61,62]. However shallow and deep seated landslides differ in terms of damage influence, size and volume [64]. Deep seated landslides generally appeared due to the relationship between natural denudation process and long-term rainfall, whereas, shallow landslides are related to short high-intensity rainfall [64]. Therefore, at this moment it is unknown whether high correlation between LSM difference (Figure 8a) and geological factors (faults and thrust proximity) correspond to some specific characteristic and mechanism of deep seated landslides, which are known for their strong connection with geology. Thus, in future works it is worth considering differentiation of landslide type (shallow/deep seated) in susceptibility modeling and its relation with landslide conditioning factors.

5. Conclusions

The fundamental source for LSM is landslide inventory. Unfortunately, there are still areas for which landslide inventories are not generated due to financial or reachability constraints. Thus, this study evaluated whether landslide susceptibility could be effectively assessed in such areas where landslide inventory was available for an adjacent region. Having considered the results from the two landslide susceptibility maps generated by cross-modeling, we can assert that susceptibility zones generated based on inventory located in an adjacent region will be different for 53% of the analyzed area when compared with a susceptibility map generated using landslide inventory. On the contrary, it can be estimated that 47% of the map generated based on inventory for a surrounding area will be similar to a map generated in a traditional manner (using landslide inventory for the analyzed region).

Based on a comparison of the accuracy measures for the training and validation areas, we can conclude that the cross-modeling of landslide susceptibility has great influence on the accuracy of landslide susceptibility determination. This is directly connected with sampling strategy (landslide selection for susceptibility modeling). In this study, we applied a sampling strategy completely different to that widely presented in the literature [13,14,20,55]. Namely, we performed cross-modeling based on landslides located in the cluster (Łososina/Gródek region) defined by the specific natural boundary (Rożnów Lake and Dunajec River). In the LSM literature, the landslide events used for modeling are usually randomly and evenly distributed across the study area. This allows capturing of the variety of geological conditions and the susceptibility to landslides. Therefore, in a perfect scenario, it is desirable to use landslides distributed evenly across the study area and located in various geological settings. This will introduce the effect of autocorrelation and allow the effective assessment of landslide susceptibility.

Nevertheless, when such a landslide sampling strategy is not possible due to the lack of landslide inventory, landslide susceptibility can be assess based on landslide inventory available in adjacent region. However, discrepancies between these two models exist in the areas of critical geological structures (thrust and fault proximity), and the reliability for such susceptibility zones can be low (2–3 susceptibility zone difference). Nonetheless, such areas cover only 11% of the analyzed area; thus, we can conclude that in remaining regions (89%), LSM generated by the inventory for the surrounding area can be used. Still, the low reliability of such a map in areas of critical geological structures should be borne in mind. This applies to LSM in other regions where the geology can be much more complex.
As such, the discrepancies among the LSMs generated based on the strategy presented in this study are particularly relevant given that the overestimation or underestimation of susceptibility can have crucial effects on land-use management and civil protection planning. The optimal map should be able to depict most potential landslide events and, at the same time, be effective and accurate for preventing failures in the study area. Therefore, specific landslide inventory is certainly needed to more reliably estimate landslide susceptibility in complex geological areas.

**Author Contributions:** Conceptualization, K.P.-F.; experiments, K.P.-F., N.O., M.P.; data capture, K.P.-F.; formal analysis, K.P.-F., N.O., M.P.; validation, K.P.-F.; writing—original draft preparation, K.P.-F.; writing—review and editing, K.P.-F.; supervision, K.P.-F.; funding acquisition, K.P.-F. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by the National Science Centre of Poland (Grant No. 2018/28/T/ST10/00528).

**Acknowledgments:** The authors are very grateful to Tomasz Wojciechowski from Polish National Geological Institute for providing geological data and documentation from the study area.

**Conflicts of Interest:** The authors declare no conflict of interest.

### Table A1. Probability Frequency Ratio Indexes Calculated for each LCFs Based on SOPO Database and Gródek Study Area.

| Factors                | Class             | Pixels in Domain | Pixels of Landslides | FR  |
|------------------------|-------------------|------------------|----------------------|-----|
|                        |                   | No %             | No %                 |     |
| **Curvature**          | −979.75—37.75     | 291,592 0.75     | 29,939 0.92          | 1.23|
|                        | −37.75—12.75      | 1,687,349 4.32   | 229,337 7.02         | 1.63|
|                        | −12.75—1.75       | 10,372,349 26.55 | 983,957 30.10        | 1.13|
|                        | −1.75—6.50        | 22,079,144 56.51 | 1,460,148 46.66      | 0.79|
|                        | 6.50—22.50        | 3,940,830 10.90  | 489,893 14.98        | 1.49|
|                        | 22.50—1140.75     | 701,338 1.79     | 75,768 2.32          | 1.29|
| **Faults Proximity [m]** | 0–765.01      | 26,053 28.99     | 2190 56.93           | 1.96|
|                        | 765.01–1586.69    | 25,432 28.30     | 1387 36.05           | 1.27|
|                        | 1586.69–2521.70   | 18,475 20.56     | 225 5.85             | 0.28|
|                        | 2521.70–3626.72   | 10,900 12.13     | 45 1.17              | 0.10|
|                        | 3626.72–5015.07   | 5775 6.43        | 0 0.00               | 0.00|
|                        | 5015.07–7253.44   | 3223 3.59        | 0 0.00               | 0.00|
| **Flow Direction**     | 1–37              | 28,223,380 72.23 | 2,615,096 79.99      | 1.11|
|                        | 37–77             | 6,242,526 15.98  | 405,102 12.39        | 0.78|
|                        | 77–109            | 13,119 0.03      | 59 0.00              | 0.05|
|                        | 109–157           | 4,572,240 11.70  | 248,918 7.61         | 0.65|
|                        | 157–214           | 13,417 0.03      | 54 0.00              | 0.05|
|                        | 214–255           | 7920 0.02        | 13 0.00              | 0.02|
| **Lake Proximity [m]** | 0–649.33         | 13,232,213 33.57 | 901,498 27.57        | 0.82|
|                        | 649.33–1593.82    | 9,813,224 24.90  | 1,046,185 31.99      | 1.29|
|                        | 1593.82–2597.33   | 7,082,092 17.97  | 776,086 23.73        | 1.32|
|                        | 2597.33–3748.42   | 4,586,819 11.64  | 378,071 11.56        | 0.99|
|                        | 3748.42–5224.17   | 3,010,943 7.64   | 145,170 4.44         | 0.58|
|                        | 5224.17–7555.87   | 1,691,373 4.29   | 23,073 0.71          | 0.16|
| **Plan Curvature**     | −701.06—45.17    | 24,815 0.06      | 2,549 0.08           | 1.23|
|                        | −45.17—22.74     | 131,431 0.34     | 16,280 0.50          | 1.48|
|                        | −22.74—11.53     | 486,180 1.24     | 70,428 2.15          | 1.73|
|                        | −11.53—5.93      | 1,258,467 3.22   | 191,990 5.87         | 1.82|
|                        | −5.93—0.32       | 13,687,923 35.03 | 1,180,094 36.10      | 1.03|
|                        | −0.32–734.06     | 23,483,786 60.10 | 1,807,901 55.30      | 0.92|
### Table A1. Cont.

| Factors            | Class | Pixels in Domain | Pixels of Landslides | FR |
|--------------------|-------|------------------|----------------------|----|
|                    | No    | %                | No                   | %  |
| **Precipitations [mm/yr]** | | | | |
| 696.41–730.70      | 4,812 | 7.70             | 1,126                | 21.15 | 2.75 |
| 730.70–756.92      | 6,353 | 10.17            | 467                  | 8.77  | 0.86 |
| 756.92–780.64      | 7,722 | 12.36            | 721                  | 13.54 | 1.10 |
| 780.64–801.77      | 9,823 | 15.39            | 267                  | 5.39  | 0.34 |
| 801.77–820.00      | 12,792| 20.47            | 995                  | 18.69 | 0.91 |
| 820.00–845.59      | 20,995| 33.59            | 1,729                | 32.47 | 0.97 |
| **Profile Curvature** | | | | |
| −868.48–−33.85     | 57,049| 0.15             | 4,023                | 0.12  | 0.84 |
| −33.85–−15.11      | 680,793| 1.74             | 67,693               | 2.07  | 1.19 |
| −15.11–−5.75       | 2,364,976| 6.05            | 297,630              | 9.10  | 0.88 |
| −5.75–3.62         | 31,249,522| 8.77          | 2,312,749            | 70.74 | 0.88 |
| 3.62–22.35         | 4,339,699| 11.11           | 552,646              | 16.90 | 1.52 |
| 22.35–612.45       | 380,561| 0.97             | 34,501               | 1.06  | 1.08 |
| **Roads Proximity [m]** | | | | |
| 0–55.03            | 14,884,008| 37.76           | 1,075,148            | 32.88 | 0.87 |
| 55.03–119.36       | 10,966,840| 27.82           | 986,543              | 30.17 | 1.08 |
| **SEI**            | | | | |
| −71.26–−17.39      | 2,171,892| 5.56            | 282,035              | 8.62  | 1.55 |
| −17.39–−6.15       | 7,539,677| 19.30            | 671,358              | 20.53 | 1.06 |
| −6.15–−2.13        | 15,204,875| 38.93           | 742,829              | 22.72 | 0.58 |
| −2.13–9.24         | 7,830,238| 20.05            | 831,721              | 25.43 | 1.27 |
| 9.24–19.89         | 5,081,182| 13.01            | 604,915              | 18.50 | 1.42 |
| 19.89–79.67        | 1,228,866| 3.15             | 137,189              | 4.20  | 1.33 |
| **Slope [°]**      | | | | |
| 0–4.46             | 9,736,000| 24.93            | 179,319              | 5.49  | 0.22 |
| 4.46–10.50         | 11,099,521| 28.43            | 935,294              | 28.61 | 1.01 |
| 10.50–16.55        | 9,289,000| 23.79            | 1,011,335            | 30.93 | 1.30 |
| 16.55–22.35        | 5,062,145| 12.96            | 660,112              | 20.19 | 1.56 |
| **Streams Proximity [m]** | | | | |
| 0–59.67            | 13,517,570| 34.42           | 1,480,964            | 45.29 | 1.32 |
| 59.67–127.28       | 10,430,942| 26.56            | 1,057,532            | 32.34 | 1.22 |
| **Thrusts Proximity [m]** | | | | |
| −506.97            | 33,107 | 28.12            | 2,165                | 34.15 | 1.21 |
| 506.97–1247.63     | 31,171 | 26.48            | 1,038                | 16.37 | 0.62 |
| **Aspect [°]**     | | | | |
| −1–56.82           | 7,170,558| 18.36            | 376,448              | 11.51 | 0.63 |
| 56.82–118.86       | 5,320,000| 13.62            | 332,974              | 10.19 | 0.75 |
| 118.86–178.09      | 5,989,026| 15.33            | 471,931              | 14.44 | 0.94 |
| **CTI**            | | | | |
| 0–4.15             | 7,790,441| 19.95            | 963,676              | 29.47 | 1.48 |
| 4.15–5.61          | 11,361,374| 29.09            | 1,126,855            | 34.46 | 1.18 |
| 5.61–7.07          | 9,614,984| 24.62            | 655,065              | 20.03 | 0.81 |
| 7.07–8.72          | 6,235,701| 16.01            | 320,192              | 9.79  | 0.61 |
| 8.72–10.86         | 3,030,027| 7.76             | 314,455              | 4.71  | 0.61 |
| 10.86–24.97        | 1,006,203| 2.58             | 50,204               | 1.54  | 0.60 |
| **IMI**            | | | | |
| −24.08–226.20      | 37,992,784| 97.28           | 3,146,601            | 96.22 | 0.99 |
| 226.2–1227.34      | 907,663| 2.32             | 102,964              | 3.15  | 1.35 |
| 1227.34–3354.77    | 118,145| 0.30             | 16,996               | 0.52  | 1.72 |
| 3354.77–7109.06    | 29,122| 0.07             | 325                  | 0.10  | 1.32 |
| 7109.056–14,742.77 | 6782 | 0.02              | 230                  | 0.01  | 0.41 |
| 14,742.77–32,012.48 | 1004 | 0.00                 | 31                  | 0.00  | 0.37 |
| Factors          | Class     | Pixels in Domain | Pixels of Landslides | FR |
|------------------|-----------|------------------|----------------------|----|
|                  |           | No %             | No %                 | FR |
| **NDVI**         |           |                  |                      |    |
| −0.55—−0.11      | 15,232    | 3.90             | 0                    | 0.00|
| −0.11—−0.12      | 13,774    | 3.53             | 110                  | 0.33|
| 0.12—−0.35       | 36,583    | 9.37             | 1154                 | 3.51|
| 0.35—−0.52       | 49,905    | 12.78            | 2,473                | 7.53|
| 0.52—−0.65       | 124,683   | 31.93            | 9,729                | 29.61|
| 0.65—−0.85       | 150,351   | 38.50            | 19,388               | 59.01|
|                  | 232.83—−285.05 | 10,648,847 | 27.25              | 224,023            | 6.85|
|                  | 285.05—−329.55 | 6,956,591 | 17.80              | 983,068             | 30.07|
|                  | 329.55—−374.20 | 6,966,168 | 17.83              | 879,834             | 26.91|
|                  | 374.20—−421.18 | 6,642,407 | 17.00              | 668,929             | 20.46|
|                  | 421.18—−475.72 | 5,166,608 | 13.22              | 416,263             | 12.73|
|                  | 475.72—−613.87 | 2,693,981 | 6.89               | 97,125              | 2.97|
| **Elevation [m]**|           |                  |                      |    |
|                  | Forest    | 613,416          | 35.52               | 72,349              | 55.25|
|                  | Water     | 122,254          | 7.08                | 26                  | 0.02|
|                  | Buildings | 342,929          | 19.86               | 22,149              | 16.91|
|                  | Bare earth (agriculture) | 165,758 | 9.60               | 6456              | 4.93|
|                  | Agricultural Areas | 482,418 | 27.94              | 29,965              | 22.88|
| **Land Cover**   |           |                  |                      |    |
| 1—Quaternary Units | 15,545 | 20.52          | 27.00               | 0.42      | 0.02|
| 2—Silesian Nappe (Tertiary period—Palaeocene) | 27,017 | 35.66       | 2969                | 45.97      | 1.29|
| 3—Silesian Nappe (Upper Cretaceous) | 14,342 | 18.93      | 854                 | 13.22      | 0.70|
| 4—Silesian Nappe (Lower Cretaceous) | 482 | 0.64          | 0                   | 0.00       | 0.00|
| 5—Under Magura Nappe Dukielskie series (Tertiary period—Palaeogene) | 1827 | 2.41        | 53                   | 0.82       | 0.34|
| 6—Grybów and Michalczowej Unit (Tertiary period—Palaeogene) | 9316 | 12.30     | 930                 | 14.40      | 1.17|
| 7—Magura Nappe (Tertiary period—Palaeogene) | 7241 | 9.56       | 1625                | 25.16      | 2.63|
| **Tectonics**    |           |                  |                      |    |
| 3—gravel, sands and clays, ore drogs of the valley bottoms (Quaternary) | 8162 | 10.76     | 18                  | 0.28       | 0.03|
| 4—clay, slits with admixture pf sands and alluvial soils, river sands and gasses of flooding and overflow terraces 1—5 m on the riverbank (Quaternary) | 3585 | 4.73      | 0                   | 0.00       | 0.00|
| 5—rock rubbles in situ (Quaternary) | 53 | 0.07       | 0                   | 0.00       | 0.00|
| 6—sands and weathering clays (Quaternary) | 371 | 0.49     | 4                   | 0.06      | 0.13|
| 7—clays, sands, clays, sometimes with congregational and diluvial rubble (Quaternary) | 277 | 0.37      | 0                   | 0.00       | 0.00|
| 9—loese-like clays (Quaternary) | 139 | 0.18     | 0                   | 0.00       | 0.00|
| 10—gravel, sands and river clays, erosive and storage terraces 6—13 m on the riverbank (Quaternary) | 2634 | 3.47    | 5                   | 0.08       | 0.02|
| 11—gravel, sands and river clays, erosive and storage terraces 15—30 m on the riverbank (Quaternary) | 228 | 0.30    | 0                   | 0.00       | 0.00|
| 12—boulders, gravel and water type sand (Quaternary) | 96 | 0.13     | 0                   | 0.00       | 0.00|
| Factors                                                                 | Class                                                                                     | Pixels in Domain | Pixels of Landslides | FR |
|------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|------------------|----------------------|----|
|                                                                        | No  | %  | No  | %  | FR |
| 22—shale and sandstones (Tertiary period—Paleocene)                    | 1771 | 2.34 | 54  | 0.84 | 0.36 |
| 23—darkish limestone (Tertiary period—Paleocene)                       | 21  | 0.03 | 0   | 0.00 | 0.00 |
| 24—medium-thick and semi-thin sandstone and shale (Tertiary period—Paleocene) | 12,740 | 16.80 | 457 | 7.08 | 0.42 |
| 25—shale, sandstone, chert, marl, and conglomerate-menilite layers (Tertiary period—Paleocene) | 675  | 0.89 | 90  | 1.39 | 1.57 |
| 26—globigerina marl (Tertiary period—Paleocene)                        | 85  | 0.11 | 38  | 0.59 | 5.25 |
| 27—sandstone and shale—hieroglyph layers (Tertiary period—Paleocene)  | 3029 | 3.99 | 1096 | 16.97 | 4.25 |
| 28—sandstone and shale—heavy type sandstone (Tertiary period—Paleocene) | 2871 | 3.79 | 517  | 8.01 | 2.11 |
| 29—shale with thick-bedded and medium-bedded sandstone inserts (Tertiary period—Paleocene) | 637  | 0.84 | 106 | 1.64 | 1.95 |
| 30—sandstone and conglomerate—upper Istebna sandstone (Tertiary period—Paleocene) | 1308 | 1.72 | 111 | 1.72 | 1.00 |
| 31—shale with thin-bedded sandstone inserts (Tertiary period—Paleocene) | 2430 | 3.20 | 309 | 4.78 | 1.49 |
| 32—Istebna shale with lower layers from upper Istebna (Upper Cretaceous) | 1510 | 1.99 | 191 | 2.96 | 1.49 |
| 33—sandstone and conglomerate—lower Istebna layers (Upper Cretaceous)  | 11,383 | 15.01 | 630 | 9.76 | 0.65 |
| 34—thin, thick and medium-bedded sandstone, seated conglomerate—unseparated Godulskie layers (Upper Cretaceous) | 2959 | 3.90 | 224 | 3.47 | 0.89 |
| 39—Rzewów shales (Lower Cretaceous)                                   | 58  | 0.08 | 0   | 0.00 | 0.00 |
| 40—sandstone-Grodziskie layers (Lower Cretaceous)                      | 119 | 0.16 | 0   | 0.00 | 0.00 |
| 41—shale with thin-bedded sandstone inserts—upper Cieszyń shales (Lower Cretaceous) | 305 | 0.40 | 0   | 0.00 | 0.00 |
| 42—thick-bedded sandstone—Cergowa sandstone (Tertiary period—Palaeogene) | 1406 | 1.85 | 53  | 0.82 | 0.44 |
| 43—shales menilite and lower Cergowa mar (Tertiary period—Palaeogene)   | 341 | 0.45 | 0   | 0.00 | 0.00 |
| 44—shales or shale and sandstone—hieroglyphs and green shale (Tertiary period—Palaeogene) | 80 | 0.11 | 0 | 0.00 | 0.00 |
### Table A1. Cont.

| Factors | Class | Pixels in Domain | Pixels of Landslides | FR |
|---------|-------|------------------|----------------------|----|
|         |       | No %             | No %                 |    |
| 45      | tylawskie limestone (Tertiary period—Palaeogene) | 4650 | 6.13 | 490 | 7.59 | 1.24 |
| 46      | Sandstone and shale (Tertiary period—Palaeogene) | 51 | 0.07 | 0 | 0.00 | 0.00 |
| 47      | Shale, chert, sandstone—Grybowski layers (Tertiary period—Palaeogene) | 3468 | 4.57 | 205 | 3.17 | 0.69 |
| 48      | Organodetic limestone and sandstone—Luzafskie limestone and Michalczowej sandstone (Tertiary period—Palaeogene) | 325 | 0.43 | 36 | 0.56 | 1.30 |
| 49      | marn shale, sandstone, lower Grybowski marl (Tertiary period—Palaeogene) | 284 | 0.37 | 0 | 0.00 | 0.00 |
| 50      | shale and sandstone—hieroglyph layers (Tertiary period—Palaeogene) | 391 | 0.52 | 199 | 3.08 | 5.98 |
| 51      | spotted shale (Tertiary period—Palaeogene) | 147 | 0.19 | 0 | 0.00 | 0.00 |
| 52      | thin and medium-bedded sandstones and shales—layers of Jawoveret/inoceramic in biotite facies (Tertiary period—Palaeogene) | 60 | 0.08 | 0 | 0.00 | 0.00 |
| 53      | sandstone and shale—Magurian layers in glauconite faction (Tertiary period—Palaeogene) | 151 | 0.20 | 0 | 0.00 | 0.00 |
| 54      | chert, Pelic limestone (Tertiary period—Palaeogene) | 562 | 0.74 | 0 | 0.00 | 0.00 |
| 56      | Częstochowa sandstones in the Magura sandstone form of Wojakowa (Tertiary period—Palaeogene) | 835 | 1.10 | 0 | 0.00 | 0.00 |
| 59      | spotted shale (Tertiary period—Palaeogene) | 779 | 1.03 | 8 | 0.12 | 0.12 |
| 60      | medium and thin-bedded sandstones and shales—layers of Kanina (Tertiary period—Palaeogene) | 1783 | 2.35 | 772 | 11.95 | 5.08 |
| 63      | marl and spotted shale (Tertiary period—Palaeogene) | 3071 | 4.05 | 845 | 13.08 | 3.23 |
| 3       | medium grassland complex | 73,017 | 4.65 | 5,034 | 3.83 | 0.82 |
| 2       | grassland weak and very weak | 469 | 0.03 | 171 | 0.13 | 4.35 |
| 8       | strong grain and fodder complex | 69,232 | 4.41 | 4639 | 3.53 | 0.80 |
| 10      | mountains wheat complex | 188,272 | 12.00 | 1078 | 0.82 | 0.07 |
| 11      | mountainous grain complex | 573,446 | 36.54 | 52,866 | 40.20 | 1.10 |
| 13      | oat fodder mountainous complex | 4801 | 0.31 | 483 | 0.37 | 1.20 |
| 14      | Arable soils intended for grassland | 10,277 | 0.65 | 4679 | 3.56 | 5.43 |
| 20      | forest | 264,201 | 16.83 | 46,219 | 35.14 | 2.09 |
| 21      | barren | 9995 | 0.64 | 0 | 0.00 | 0.00 |
| 23      | forest clay sands | 137,252 | 8.75 | 11,827 | 8.99 | 1.03 |
Table A1. Cont.

| Factors Class | Pixels in Domain | Pixels of Landslides | FR |
|---------------|-----------------|----------------------|----|
| 24—agriculturally unsuitable soils suitable for afforestation | 1055 0.07 | 673 0.51 | 7.61 |
| 25—agricultural areas | 3,549 0.23 | 416 0.32 | 1.40 |
| 26—water | 215,609 13.74 | 1695 1.29 | 0.09 |
| 33—defective wheat complex | 18,236 1.16 | 1730 1.32 | 1.13 |

Appendix B

Table A2. Probability Frequency Ratio Indexes Calculated for each LCFs Based on SOPO Database and Łososina Study Area.

| Factors Class | Pixels in Domain | Pixels of Landslides | FR |
|---------------|-----------------|----------------------|----|
| −979.75—37.75 | 291,592 0.75 | 23,642 1.12 | 1.51 |
| −37.75—12.75 | 1,687,349 4.32 | 168,559 8.02 | 1.86 |
| −12.75—1.75 | 10,379,349 26.55 | 635,081 30.21 | 1.14 |
| −1.75—0.32 | 22,079,144 56.51 | 880,022 41.86 | 0.74 |
| 0—765.01 | 26,053 28.99 | 660 20.65 | 0.71 |
| 765.01—1586.69 | 25,482 28.30 | 749 23.44 | 0.83 |
| 1586.69—2521.70 | 18,475 20.56 | 1227 38.39 | 1.17 |
| 2521.70—3626.72 | 10,900 12.13 | 498 15.58 | 1.28 |
| 3626.72—5015.07 | 5775 6.43 | 62 1.94 | 0.30 |
| 5015.07—7253.44 | 3223 3.59 | 0 0.00 | 0.00 |
| −701.06—45.17 | 24,815 0.06 | 2138 0.10 | 0.43 |
| −45.17—22.74 | 131,431 0.34 | 12,925 0.61 | 1.09 |
| −22.74—11.53 | 486,180 1.24 | 52,705 2.51 | 1.42 |
| −11.53—5.93 | 1,258,467 3.22 | 135,930 6.70 | 1.07 |
| −5.93—0.32 | 13,687,923 35.03 | 747,311 35.55 | 1.01 |
| −0.32—734.06 | 23,483,786 60.10 | 1,151,647 54.78 | 0.91 |
| −22.35—612.45 | 380,561 0.97 | 27,293 1.30 | 1.33 |

Precipitations [mm/yr]

| 696.41—730.70 | 4812 7.70 | 9 0.26 | 0.03 |
| 730.70—756.92 | 6353 10.17 | 285 8.23 | 0.81 |
| 756.92—780.64 | 7722 12.36 | 0 0.00 | 0.00 |
| 780.64—801.77 | 9823 15.72 | 817 23.58 | 1.50 |
| 801.77—820.00 | 12,792 20.47 | 1427 41.18 | 2.01 |
| 820.00—845.59 | 20,995 33.59 | 927 26.75 | 0.80 |

Profile Curvature

| −886.48—33.85 | 57,049 0.15 | 3716 0.18 | 1.21 |
| −33.85—15.11 | 680,793 1.74 | 52,138 2.48 | 1.42 |
| −15.11—5.75 | 2,364,978 6.05 | 211,106 10.04 | 1.66 |
| −5.75—3.62 | 31,249,522 79.98 | 1,417,790 67.44 | 0.84 |
| 3.62—22.35 | 4,339,699 11.11 | 390,276 18.56 | 1.67 |
| 22.35—612.45 | 380,561 0.97 | 27,293 1.30 | 1.33 |
| Factors        | Class | Pixels in Domain No | %   | Pixels of Landslides No | %   | FR  |
|---------------|-------|---------------------|-----|-------------------------|-----|-----|
| Roads Proximity [m] | 0–55.03 | 14,884,008 | 37.76 | 723,844 | 34.47 | 0.91 |
|               | 55.03–119.36 | 10,966,840 | 27.82 | 705,339 | 33.54 | 1.21 |
|               | 119.36–200.64 | 7,044,541 | 17.87 | 461,458 | 21.94 | 1.23 |
|               | 200.64–310.73 | 3,746,656 | 9.51 | 165,853 | 7.89 | 0.83 |
|               | 310.73–461.87 | 1,920,345 | 4.87 | 42,200 | 2.01 | 0.41 |
|               | 461.87–783.52 | 854,274 | 2.17 | 312 | 0.15 | 0.07 |
|               | −71.26–−17.39 | 9,736,000 | 24.93 | 82,122 | 3.91 | 0.16 |
|               | −17.39–−6.15 | 11,099,321 | 28.43 | 494,938 | 23.54 | 0.83 |
|               | −6.15–1.23 | 7,694,317 | 19.59 | 330,290 | 15.72 | 0.80 |
|               | 1.23–9.24 | 15,204,875 | 38.93 | 407,265 | 19.37 | 0.50 |
|               | 9.24–19.89 | 7,830,238 | 20.05 | 536,617 | 25.52 | 1.27 |
|               | 19.89–79.67 | 5,081,182 | 13.01 | 475,949 | 22.64 | 1.74 |
| Slope [°]    | 0.000074–4.46 | 9,736,000 | 24.93 | 82,122 | 3.91 | 0.16 |
| Streams Proximity [m] | 0–59.67 | 13,517,570 | 34.42 | 942,196 | 44.85 | 1.30 |
|               | 59.67–127.28 | 10,430,942 | 26.56 | 641,522 | 30.54 | 1.15 |
|               | 127.28–206.81 | 7,694,317 | 19.59 | 330,290 | 15.72 | 0.80 |
|               | 206.81–310.66 | 4,816,996 | 12.27 | 144,706 | 6.89 | 0.56 |
|               | 310.66–468.80 | 1,987,450 | 5.06 | 41,752 | 1.99 | 0.39 |
|               | 468.80–821.72 | 824,373 | 2.10 | 392 | 0.02 | 0.01 |
| Thrusts Proximity [m] | 0–556.97 | 33,107 | 28.12 | 1537 | 36.34 | 1.29 |
|               | 556.97–1247.63 | 31,171 | 26.48 | 1306 | 30.88 | 1.17 |
|               | 1247.63–2027.39 | 22,416 | 19.04 | 917 | 21.68 | 1.14 |
|               | 2027.39–2940.84 | 15,252 | 12.96 | 348 | 8.23 | 0.64 |
|               | 2940.84–3987.95 | 9789 | 8.32 | 121 | 2.86 | 0.34 |
| Aspect [°]   | 0–56.82 | 7,170,558 | 18.36 | 280,161 | 13.33 | 0.73 |
| CTI          | 56.82–118.86 | 5,320,000 | 13.62 | 458,783 | 21.82 | 1.60 |
|               | 118.86–178.09 | 5,986,026 | 15.33 | 561,221 | 26.70 | 1.74 |
|               | 178.09–235.91 | 7,716,443 | 19.76 | 373,687 | 17.78 | 0.90 |
|               | 235.91–297.95 | 6,014,624 | 15.40 | 41,752 | 1.99 | 0.39 |
|               | 297.95–360 | 6,839,650 | 17.52 | 198,562 | 9.45 | 0.54 |
| IMI          | −1–56.82 | 7,170,558 | 18.36 | 280,161 | 13.33 | 0.73 |
|               | 56.82–118.86 | 5,320,000 | 13.62 | 458,783 | 21.82 | 1.60 |
|               | 118.86–178.09 | 5,986,026 | 15.33 | 561,221 | 26.70 | 1.74 |
|               | 178.09–235.91 | 7,716,443 | 19.76 | 373,687 | 17.78 | 0.90 |
|               | 235.91–297.95 | 6,014,624 | 15.40 | 41,752 | 1.99 | 0.39 |
|               | 297.95–360 | 6,839,650 | 17.52 | 198,562 | 9.45 | 0.54 |
| NDVI         | −0.55–−0.11 | 15,232 | 3.90 | 0 | 0.00 | 0.00 |
|               | −0.11–0.12 | 13,774 | 3.53 | 0 | 0.00 | 0.00 |
|               | 0.12–0.35 | 36,583 | 9.37 | 474 | 2.25 | 0.24 |
|               | 0.35–0.52 | 49,905 | 12.78 | 1297 | 6.16 | 0.48 |
|               | 0.52–0.65 | 124,683 | 31.93 | 5938 | 28.21 | 0.88 |
|               | 0.65–0.85 | 150,351 | 38.50 | 13,342 | 63.38 | 1.65 |
| Elevation [m] | −24.08–226.20 | 37,992,784 | 97.28 | 2,014,350 | 95.81 | 0.98 |
|               | 226.2–1227.34 | 2862.32 | 7.22 | 69,553 | 3.31 | 1.42 |
|               | 1227.34–3354.77 | 118,145 | 0.30 | 13,966 | 0.66 | 2.20 |
|               | 3354.77–7109.06 | 29,122 | 0.07 | 3761 | 0.18 | 2.40 |
|               | 7109.06–14,742.77 | 6782 | 0.02 | 717 | 0.03 | 1.96 |
|               | 14,742.77–32,012.48 | 1004 | 0.00 | 72 | 0.00 | 1.33 |

Table A2. Cont.
### Table A2. Cont.

| Factors         | Class                                | Pixels in Domain No | Pixels of Landslides No | FR  |
|-----------------|--------------------------------------|---------------------|-------------------------|-----|
| **Land Cover**  |                                      |                     |                         |     |
|                 | Forest                               | 613,416             | 72,349                  | 1.56|
|                 | Water                                | 122,254             | 26                      | 0.02|
|                 | Buildings                            | 342,929             | 22,149                  | 0.85|
|                 | Bare earth (agriculture)             | 165,758             | 6456                    | 0.51|
|                 | Agricultural Areas                   | 482,418             | 29,965                  | 0.82|
|                 |                                      |                     |                         |     |
| **Tectonics**   | 1—Quaternary Units                   | 15,545              | 27.00                   | 0.42|
|                 | 2—Silesian Nappe (Tertiary period—Paleocene) | 27,017             | 2,969                   | 0.42|
|                 | 3—Silesian Nappe (Upper Cretaceous)  | 14,342              | 854                     | 0.70|
|                 | 4—Silesian Nappe (Lower Cretaceous)  | 482                 | 0                       | 0.00|
|                 | 5—Under Magura Nappe                  | 1827                | 53                      | 0.82|
|                 | Dukielskie series (Tertiary period—Palaeogene) |                     |                         |     |
|                 | 6—Grybów and Michalczowęż Unit        | 9316                | 930                     | 1.17|
|                 | (Tertiary period—Palaeogene)         |                     |                         |     |
|                 | 7—Magura Nappe (Tertiary period—Palaeogene) | 7241               | 1625                    | 2.63|
|                 | 3—gravel, sands and clays, ore dregs of the valley bottoms (Quaternary) | 8162               | 18                      | 0.28|
|                 | 4—clay, slits with admixture of sands and alluvial soils, river sands and gases of flooding and overflow terraces 1–5 m on the riverbank (Quaternary) | 3585               | 0                       | 0.00|
|                 | 5—rock rubbles in situ (Quaternary)  | 53                  | 0                       | 0.00|
|                 | 6—sands and weathering clays (Quaternary) | 371                | 4                       | 0.06|
|                 | 7—clays, sands, clays, sometimes with congregational and diluvial rubble (Quaternary) | 277                | 0                       | 0.00|
|                 | 9—loess-like clays (Quaternary)      | 139                 | 0                       | 0.00|
|                 | 10—gravel, sands and river clays, erosive and storage terraces 6–13 m on the riverbank (Quaternary) | 2634               | 5                       | 0.08|
|                 | 11—gravel, sands and river clays, erosive and storage terraces. 15–30 m (Quaternary) on the riverbank (Quaternary) | 228                | 0                       | 0.00|
|                 | 12—boulders, gravel and water type sand (Quaternary) | 96                 | 0                       | 0.00|
|                 | 22—shale and sandstones (Tertiary period—Paleocene) | 1771               | 54                      | 0.84|
|                 | 23—darkish limestone (Tertiary period—Paleocene) | 21                 | 0                       | 0.00|
|                 | 24—medium-thick and semi-thin sandstone and shale (Tertiary period—Paleocene) | 12,740             | 457                     | 7.08|
|                 | 25—shale, sandstone, chert, marl, and conglomerate-menilite layers (Tertiary period—Paleocene) | 675                | 90                      | 1.39|
|                 | 26—globigerina marl (Tertiary period—Paleocene) | 85                 | 38                      | 0.59|

| **Lithostratigraphic unit** |                                      |                     |                         |     |
|-----------------------------|--------------------------------------|---------------------|-------------------------|-----|
| 1—Quaternary Units          | 15,545                               | 20.52               | 27.00                   | 0.42|
| 2—Silesian Nappe (Tertiary period—Paleocene) | 27,017                             | 35.66               | 2,969                   | 0.42|
| 3—Silesian Nappe (Upper Cretaceous) | 14,342                             | 18.93               | 854                     | 0.70|
| 4—Silesian Nappe (Lower Cretaceous) | 482                                | 0.64                | 0                       | 0.00|
| 5—Under Magura Nappe Dukielskie series (Tertiary period—Palaeogene) | 1827                               | 2.41                | 53                      | 0.82|
| 6—Grybów and Michalczowęż Unit (Tertiary period—Palaeogene) | 9316                               | 12.30               | 930                     | 1.17|
| 7—Magura Nappe (Tertiary period—Palaeogene) | 7241                               | 9.56                | 1625                    | 2.63|
| 3—gravel, sands and clays, ore dregs of the valley bottoms (Quaternary) | 8162                               | 10.76               | 18                      | 0.28|
| 4—clay, slits with admixture of sands and alluvial soils, river sands and gases of flooding and overflow terraces 1–5 m on the riverbank (Quaternary) | 3585                               | 4.73                | 0                       | 0.00|
| 5—rock rubbles in situ (Quaternary) | 53                                  | 0.07                | 0                       | 0.00|
| 6—sands and weathering clays (Quaternary) | 371                                | 0.49                | 4                       | 0.06|
| 7—clays, sands, clays, sometimes with congregational and diluvial rubble (Quaternary) | 277                                | 0.37                | 0                       | 0.00|
| 9—loess-like clays (Quaternary) | 139                                 | 0.18                | 0                       | 0.00|
| 10—gravel, sands and river clays, erosive and storage terraces 6–13 m on the riverbank (Quaternary) | 2634                               | 3.47                | 5                       | 0.08|
| 11—gravel, sands and river clays, erosive and storage terraces. 15–30 m (Quaternary) on the riverbank (Quaternary) | 228                                | 0.30                | 0                       | 0.00|
| 12—boulders, gravel and water type sand (Quaternary) | 96                                  | 0.13                | 0                       | 0.00|
| 22—shale and sandstones (Tertiary period—Paleocene) | 1771                               | 2.34                | 54                      | 0.84|
| 23—darkish limestone (Tertiary period—Paleocene) | 21                                 | 0.03                | 0                       | 0.00|
| 24—medium-thick and semi-thin sandstone and shale (Tertiary period—Paleocene) | 12,740                             | 16.80               | 457                     | 7.08|
| 25—shale, sandstone, chert, marl, and conglomerate-menilite layers (Tertiary period—Paleocene) | 675                                | 0.89                | 90                      | 1.39|
| 26—globigerina marl (Tertiary period—Paleocene) | 85                                  | 0.11                | 38                      | 0.59|
| Factors | Class | Pixels in Domain No | % | Pixels of Landslides No | % | FR |
|---------|-------|---------------------|----|-------------------------|----|----|
| 27      | sandstone and shale—hieroglyph layers (Tertiary period—Paleocene) | 3029 | 3.99 | 1096 | 16.97 | 4.25 |
| 28      | sandstone and shale—heavy type sandstone (Tertiary period—Paleocene) | 2871 | 3.79 | 517 | 8.01 | 2.11 |
| 29      | shale with thick-bedded and medium-bedded sandstone inserts (Tertiary period—Paleocene) | 637 | 0.84 | 106 | 1.64 | 1.95 |
| 30      | sandstone and conglomerate—upper Istebna sandstone (Tertiary period—Paleocene) | 1308 | 1.72 | 111 | 1.72 | 1.00 |
| 31      | shale with thin-bedded sandstone inserts (Tertiary period—Paleocene) | 2430 | 3.20 | 309 | 4.78 | 1.49 |
| 32      | Istebna shale with lower layers from upper Istebna (Upper Cretaceous) | 1510 | 1.99 | 191 | 2.96 | 1.49 |
| 33      | sandstone and conglomerate—lower Istebna layers (Upper Cretaceous) | 11,383 | 15.01 | 630 | 9.76 | 0.65 |
| 34      | thin, thick and medium-bedded sandstone, seated conglomerate—unseparated Godulskie layers (Upper Cretaceous) | 2959 | 3.90 | 224 | 3.47 | 0.89 |
| 39      | Rzewków shales (Lower Cretaceous) | 58 | 0.08 | 0 | 0.00 | 0.00 |
| 40      | sandstone-Grodziskie layers (Lower Cretaceous) | 119 | 0.16 | 0 | 0.00 | 0.00 |
| 41      | shale with thin-bedded sandstone inserts—upper Cieszyn shales (Lower Cretaceous) | 305 | 0.40 | 0 | 0.00 | 0.00 |
| 42      | thick-bedded sandstone—Cergowa sandstone (Tertiary period—Palaeogene) | 1406 | 1.85 | 53 | 0.82 | 0.44 |
| 43      | shales menilite and lower Cergowa mar (Tertiary period—Palaeogene) | 341 | 0.45 | 0 | 0.00 | 0.00 |
| 44      | shales or shale and sandstone—hieroglyphs and green shale (Tertiary period—Palaeogene) | 80 | 0.11 | 0 | 0.00 | 0.00 |
| 45      | tylawskie limestone (Tertiary period—Palaeogene) | 4650 | 6.13 | 490 | 7.59 | 1.24 |
| 46      | Sandstone and shale (Tertiary period—Palaeogene) | 4650 | 6.13 | 490 | 7.59 | 1.24 |
| 47      | Sandstone and shale—hieroglyph layers (Tertiary period—Palaeogene) | 3468 | 4.57 | 205 | 3.17 | 0.69 |
| 48      | Organodetic limestone and sandstone—Luzarskie limestone and Michalczowej sandstone (Tertiary period—Palaeogene) | 325 | 0.43 | 36 | 0.56 | 1.30 |
| 49      | marn shale, sandstone, lower Grybowski marl (Tertiary period—Palaeogene) | 284 | 0.37 | 0 | 0.00 | 0.00 |
### Table A2. Cont.

| Factors                                                                 | Class                                                                 | Pixels in Domain No | Pixels in Domain % | Pixels of Landslides No | Pixels of Landslides % | FR  |
|------------------------------------------------------------------------|----------------------------------------------------------------------|---------------------|---------------------|------------------------|------------------------|-----|
| 50—shale and sandstone–mieroglyph layers (Tertiary period—Palaeogene) |                                                                      | 391                 | 0.52                | 199                    | 3.08                   | 5.98|
| 51—spotted shale (Tertiary period—Palaeogene)                         |                                                                      | 147                 | 0.19                | 0                      | 0.00                   | 0.00|
| 52—thin and medium-bedded sandstones and shales—layers of Jawoveret/inoceramic in biotite facies (Tertiary period—Palaeogene) |                                                                      | 60                  | 0.08                | 0                      | 0.00                   | 0.00|
| 53—sandstone and shale-Magura layers in glauconite faction (Tertiary period—Palaeogene) |                                                                      | 151                 | 0.20                | 0                      | 0.00                   | 0.00|
| 56—chert, Pelic limestone (Tertiary period—Palaeogene)                 |                                                                      | 562                 | 0.74                | 0                      | 0.00                   | 0.00|
| 59—Ciezkowice sandstones in the Magura sandstone form of Wojakowa (Tertiary period—Palaeogene) |                                                                      | 835                 | 1.10                | 0                      | 0.00                   | 0.00|
| 60—spotted shale (Tertiary period—Palaeogene)                         |                                                                      | 779                 | 1.03                | 8                      | 0.12                   | 0.12|
| 62—medium and thin-bedded sandstones and shales—layers of Kanina (Tertiary period—Palaeogene) |                                                                      | 1783                | 2.35                | 772                    | 11.95                  | 5.08|
| 63—marl and spotted shale (Tertiary period—Palaeogene)                |                                                                      | 3071                | 4.05                | 845                    | 13.08                  | 3.23|
| Soil suitability                                                       | 2—medium grassland complex                                           | 73,017              | 4.65                | 7861                   | 9.29                   | 2.00|
|                                                                        | 3—grassland weak and very weak                                       | 469                 | 0.03                | 0                      | 0.00                   | 0.00|
|                                                                        | 8—strong grain and fodder complex                                     | 69,232              | 4.41                | 4494                   | 5.31                   | 1.20|
|                                                                        | 10—mountains wheat complex                                            | 188,272             | 12.00               | 3672                   | 4.34                   | 0.36|
|                                                                        | 11—mountainous grain complex                                          | 573,446             | 36.54               | 28,503                  | 33.68                  | 0.92|
|                                                                        | 13—oat fodder mountainous complex                                     | 4801                | 0.31                | 134                    | 0.16                   | 0.52|
|                                                                        | 14—Arable soils intended for grassland                                | 10,277              | 0.65                | 1328                   | 1.57                   | 2.40|
|                                                                        | 20—forest                                                             | 264,201             | 16.83               | 21,568                  | 25.49                  | 1.51|
|                                                                        | 21—barren                                                             | 9995                | 0.64                | 96                     | 0.11                   | 0.18|
|                                                                        | 23—forest clay sands                                                  | 137,252             | 8.75                | 12,645                  | 14.94                  | 1.71|
|                                                                        | 24—agriculturally unsuitable soils suitable for afforestation         | 1055                | 0.07                | 0                      | 0.00                   | 0.00|
|                                                                        | 25—agricultural areas                                                 | 3549                | 0.23                | 0                      | 0.00                   | 0.00|
|                                                                        | 26—water                                                              | 215,609             | 13.74               | 1099                   | 1.30                   | 0.09|
|                                                                        | 33—defective wheat complex                                            | 18,236              | 1.16                | 3223                   | 3.81                   | 3.28|

### References

1. Cruden, D.M.; Varnes, D.J. Landslide types and processes. In Landslides: Investigation and Mitigation; Turner, A.K., Schuster, R.L., Eds.; Transportation Research Board: Washington, DC, USA, 1996.
2. Lin, L.; Lin, Q.; Wang, Y. Landslide susceptibility mapping on a global scale using the method of logistic regression. Nat. Hazards Earth Syst. Sci. 2017, 18, 1411–1424. [CrossRef]
3. Arabameri, A.; Pradhan, B.; Rezaei, K.; Sohrabi, M.; Kalantari, Z. GIS-based landslide susceptibility mapping using numerical risk factor bivariate model and its ensemble with linear multivariate regression and boosted regression tree algorithms. *J. Mt. Sci.* 2019, 16, 595–618. [CrossRef]

4. Nicodemo, G.; Peduto, D.; Ferlisi, S.; Gallù, G.; Borrelli, L.; Fornaro, G.; Reale, D. Analysis of building vulnerability to slow-moving landslides via A-DInSAR and damage survey data. In *Advancing Culture of Living with Landslides*; Mikos, M., Tiwari, Y., Sassa, Y., Eds.; Springer: Cham, Switzerland, 2017; pp. 889–907. [CrossRef]

5. Borrelli, L.; Nicodemo, G.; Ferlisi, S.; Peduto, D.; Di Nocera, S.; Gallù, G. Geology, slow-moving landslides, and damges to buildings in the Veribacaro area (North-Western Calabria Region, Southern Italy). *J. Maps* 2018, 14, 32–44. [CrossRef]

6. Nadim, F.; Kjekstad, O.; Peduzzi, P.; Herold, C.; Jaedicke, C. Global landslide and avalanche hotspots. *Landslides* 2006, 3, 159–173. [CrossRef]

7. Poprawa, D.; Rączkowski, W. Osuwiska Karpat. *Przegląd Geol.* 2014, 51, 685–692. (In Polish)

8. Borkowski, A.; Perski, Z.; Wojciechowski, T.; Józkoń, G.; Wójcik, A. Landslides mapping in Roznow Lake vicinity, Poland using airborne laser scanning data. *Acta Geodaetica Geomatica*. 2011, 8, 325–333.

9. Wojciechowski, T.; Borkowski, A.; Perski, Z.; Wójcik, A. Airborne laser scanning data in landslide studies at the example of the Zbyszycze landslide (Outer Carpathians). *Przegląd Geol.* 2012, 60, 95–102. (In Polish)

10. Cascini, L.; Ciurleo, M.; Di Nocera, S.; Gallù, G. A new–old approach for shallow landslide analysis and susceptibility zoning in fine-grained weathered soils of southern Italy. *Geomorphology* 2015, 241, 371–381. [CrossRef]

11. Ciurleo, M.; Mandaglio, M.C.; Moraci, N. Landslide susceptibility assessment by TRIGRS in a frequently affected shallow instability area. *Landslides* 2019, 16, 175–188. [CrossRef]

12. Guzzetti, F. Landslide Hazard and Risk Assessment. Ph.D. Thesis, Mathematisch-Naturwissenschaftlichen Fakultät der Rheinischen Friedrich-Wilhelms-University of Bonn, Bonn, Germany, 2006.

13. Arabameri, A.; Saha, S.; Roy, J.; Chen, W.; Blaschke, T.; Tien Bui, D. Landslide susceptibility evaluation and management using different machine learning methods in the Gallicash River Watershed, Iran. *Remote Sens.* 2020, 12, 475. [CrossRef]

14. Pawluszek, K.; Borkowski, A. Impact of DEM-derived factors and analytical hierarchy process on landslide susceptibility mapping in the region of Rożnów Lake, Poland. *Nat. Hazards* 2017, 86, 919–952. [CrossRef]

15. Paudel, U.; Oguchi, T.; Hayakawa, Y. Multi-resolution landslide susceptibility analysis using a DEM and random forest. *Int. J. Geosci.* 2016, 7, 726–743. [CrossRef]

16. Saadatkhan, N.; Kassim, A.; Lee, L.M. Qualitative and quantitative landslide susceptibility assessments in Hulu Kelang area, Malaysia. *Electron. J. Geotech. Eng.* 2014, 19, 545–563.

17. Ciurleo, M.; Mandaglio, M.C.; Moraci, N.; Pitasi, A. A method to evaluate debris flow triggering and propagation by numerical analyses. In *Geotechnical Research for Land Protection and Development*. CNRIG 2019. *Lecture Notes in Civil Engineering*; Calvetti, F., Cotecchia, F., Galli, A., Jommi, C., Eds.; Springer: Cham, Switzerland, 2019; Volume 40, pp. 33–41.

18. Chen, W.; Xie, X.; Peng, J.; Shahabi, H.; Hong, H.; Bui, D.T.; Zhu, A.X. GIS-based landslide susceptibility evaluation using a novel hybrid integration approach of bivariate statistical based random forest method. *Catena* 2018, 164, 135–149. [CrossRef]

19. Aditian, A.; Kubota, T.; Shinohara, Y. Comparison of GIS-based landslide susceptibility models using frequency ratio, logistic regression, and artificial neural network in a tertiary region of Ambon, Indonesia. *Geomorphology* 2018, 318, 101–111. [CrossRef]

20. Razavizadeh, S.; Solaimani, K.; Massironi, M.; Kavian, A. Mapping landslide susceptibility with frequency ratio, statistical index, and weights of evidence models: A case study in northern Iran. *Environ. Earth Sci.* 2017, 76, 499. [CrossRef]

21. Lee, S.; Oh, H.J. Landslide susceptibility prediction using evidential belief function, weight of evidence and artificial neural network models. *Korean J. Remote Sens.* 2019, 35, 299–316.

22. Shirani, K.; Pasandi, M.; Arabameri, A. Landslide susceptibility assessment by dempster–shafer and index of entropy models, Sarkhoun basin, southwestern Iran. *Nat. Hazards* 2018, 93, 1379–1418. [CrossRef]

23. Kanungo, D.P.; Arora, M.K.; Sarkar, S.; Gupta, R.P. A comparative study of conventional, ANN black box, fuzzy and combined neural and fuzzy weighting procedures for landslide susceptibility zonation in Darjeeling Himalayas. *Eng. Geol.* 2006, 85, 347–366. [CrossRef]
24. Chen, W.; Pourghasemi, H.R.; Naghibi, S.A. A comparative study of landslide susceptibility maps produced using support vector machine with different kernel functions and entropy data mining models in China. *Bull. Eng. Geol. Environ.* 2018, 77, 647–664. [CrossRef]

25. Huang, Y.; Zhao, L. Review on landslide susceptibility mapping using support vector machines. *Catena* 2018, 165, 529. [CrossRef]

26. Zhang, K.; Wu, X.; Niu, R.; Yang, K.; Zhao, L. The assessment of landslide susceptibility mapping using random forest and decision tree methods in the Three Gorges Reservoir area, China. *Environ. Earth Sci.* 2018, 76, 1–20. [CrossRef]

27. Gudiyanagada Nachappa, T.; Kienberger, S.; Meena, S.R.; Hölbling, D.; Blaschke, T. Comparison and validation of per-pixel and object-based approaches for landslide susceptibility mapping. *Geomat. Nat. Hazards Risk* 2020, 11, 572–600.

28. Javier, D.N.; Kumar, L. Frequency ratio landslide susceptibility estimation in a tropical mountain region. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* 2019, 42, 173–179. [CrossRef]

29. Van Den Eeckhaut, M.; Hervás, J. State of the art of national landslide databases in Europe and their potential for assessing landslide susceptibility, hazard and risk. *Geomorphology* 2012, 139. [CrossRef]

30. Cieszkowski, M.; Waszkowska, A. Castles from the Roznowskie and Czchowskie lakes as geotouristic lapidaria and the role of the Istebna sandstones in their formation. *Geoturystyka* 2010, 21, 3–18. (In Polish)

31. Hungr, O.; Leroueil, S.; Picarelli, L. The Varnes classification of landslide types, an update. *Landslides* 2014, 11, 167–194. [CrossRef]

32. Dai, F.C.; Xu, C.; Yao, X.; Xu, L.; Tu, X.B.; Gong, Q.M. Spatial distribution of landslides triggered by the 2008 Ms 8.0 Wenchuan earthquake, China. *J. Asian Earth Sci.* 2011, 40, 883–895. [CrossRef]

33. Dou, J.; Paudel, U.; Oguchi, T.; Uchiyama, S.; Hayakavva, Y.S. Shallow and deep-seated landslide differentiation using support vector machines: A case study of the Chuetsu Area, Japan. *T err. Atmos. Ocean. Sci.* 2015, 26, 227–239. [CrossRef]

34. Roering, J.J.; Schmidt, K.M.; Stock, J.D.; Dietrich, W.E.; Montgomery, D.R. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. *Can. Geotech. J.* 2003, 40, 237–253. [CrossRef]

35. Bąk, M.; Długosz, M.; Gorczyca, E.; Kasina, Koziol, T.; Wrońska-Wałach, D.; Wyderski, P. *Map of Landslides and Areas Threatened by Mass Movements on a Scale of 1: 10000 Lososina Dolna Commune, Nowosądeckie County, Małopolskie Municipality*. Ministerstwo Środowiska: Warszawa, Poland, 2011. (In Polish)

36. Wójcik, A.; Wojciechowski, T.; Wódka, M.; Krzysiek, U. *Map of Landslides and Areas Threatened by Mass Movements on a Scale of 1: 10000 Gródek nad Dunajcem Commune, Nowosądeckie County, Małopolskie Municipality*. Ministerstwo Środowiska: Warszawa, Poland, 2015. (In Polish)

37. Gorczyca, E.; Wrońska-Wałach, D. *Explanations to the Landslides Inventory Maps and Areas Prone to Mass Movements in the Scale of 1:10000. Municipality of Lososina Dolna, District: Nowosądeckie, Province: Małopolskie*. Ministerstwo Środowiska: Warszawa, Poland, 2011. (In Polish)

38. Grabowski, K.; Mrozek, T.; Nescieruk, P.; Raczkowski, W.; Wójcik, A.; Zimnal, Z. Manual for Mapping Landslides and Areas Threatened by Mass Movements, Ministerstwo Środowiska: Warszawa, Poland, 2008. (In Polish)

39. Pawłuszek, K.; Marczak, S.; Borkowski, A.; Tarolli, P. Multi-aspect analysis of object-oriented landslide detection based on an extended set of LiDAR-derived terrain features. *ISPRS Int. J. Geo-Inf.* 2019, 8, 321. [CrossRef]

40. Pawłuszek, K.; Marczak, S.; Borkowski, A.; Tarolli, P. Multi-aspect analysis of object-oriented landslide detection based on an extended set of LiDAR-derived terrain features. *ISPRS Int. J. Geo-Inf.* 2019, 8, 321. [CrossRef]
44. Pawluszek, K.; Borkowski, A.; Tarolli, P. Sensitivity analysis of automatic landslide mapping: Numerical experiments towards the best solution. *Landslides* **2018**, *15*, 1851–1865. [CrossRef]

45. Pawluszek, K.; Borkowski, A.; Tarolli, P. Towards the optimal pixel size of DEM for automatic mapping of landslide areas. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *42*, 83–89. [CrossRef]

46. Pawluszek, K.; Borkowski, A. Landslides identification using airborne laser scanning data derived topographic terrain attributes and support vector machine classification. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *8*. [CrossRef]

47. Evans, J.S.; Oakleaf, J.; Cushman, S.A.; Theobald, D. An ArcGIS Toolbox for Surface Gradient and Geomorphometric Modeling, Version 2.0-0. Available online: [http://evansmurphy.wix.com/evansspatial](http://evansmurphy.wix.com/evansspatial) (accessed on 3 August 2020).

48. Ozdemir, A. Landslide susceptibility mapping of vicinity of Yaka Landslide (Gelendost, Turkey) using conditional probability approach in GIS. *Environ. Geol.* **2009**, *57*, 1675–1686. [CrossRef]

49. Sharma, A.; Sur, U.; Singh, P.; Rai, P.K.; Srivastava, P.K. Probabilistic landslide hazard assessment using Statistical Information Value (SIV) and GIS Techniques: A case study of Himachal Pradesh, India. In *Techniques for Disaster Risk Management and Mitigation*; John Wiley and Sons: Hoboken, NJ, USA, 2020; pp. 197–208.

50. Pokharel, B.; Thapa, P.B. Landslide susceptibility in Rasuwa District of central Nepal after the 2015 Gorkha Earthquake. *J. Nepal Geol. Soc.* **2019**, *59*, 79–88. [CrossRef]

51. Chen, W.; Sun, Z.; Han, J. Landslide susceptibility modeling using integrated ensemble weights of evidence with logistic regression and random forest models. *Appl. Sci.* **2019**, *9*, 171. [CrossRef]

52. Pawluszek, K. Landslide features identification and morphology investigation using high-resolution DEM derivatives. *Nat. Hazards* **2019**, *96*, 311–330. [CrossRef]

53. Ahmed, B.; Rahman, M.S.; Sammonds, P.; Islam, R.; Uddin, K. Application of geospatial technologies in developing a dynamic landslide early warning system in a humanitarian context: The Rohingya refugee crisis in Cox’s Bazar, Bangladesh. *Geomat. Nat. Hazards Risk* **2020**, *11*. [CrossRef]

54. Ramachandra, T.V.; Kumar, U.; Aithal, B.H.; Diwakar, P.G.; Joshi, N.V. Landslide susceptible locations in Western Ghats: Prediction through OpenModeller. In Proceedings of the 26th Annual In-House Symposium on Space Science and Technology, Bangalore, India, 28–29 January 2010; pp. 65–74.

55. Abedini, M.; Ghasemyan, B.; Mogaddam, M.R. Landslide susceptibility mapping in Bijar city, Kurdistan Province, Iran: A comparative study by logistic regression and AHP models. *Environ. Earth Sci.* **2017**, *76*, 308. [CrossRef]

56. Jenks, G.F. The data model concept in statistical mapping. *Int. Yearb. Cartogr.* **1967**, *7*, 186–190.

57. Guzzetti, F.; Reichenbach, P.; Ardizzone, F.; Cardinali, M.; Galli, M. Estimating the quality of landslide susceptibility models. *Geomorphology* **2006**, *81*, 166–184. [CrossRef]

58. Van Den Eeckhaut, M.; Hervás, J.; Jaedicke, C.; Malet, J.P.; Montanarella, L.; Nadim, F. Statistical modelling of Europe-wide landslide susceptibility using limited landslide inventory data. *Landslides* **2012**, *8*, 357–369. [CrossRef]

59. Armstrong, M.P.; Xiao, N.; Bennett, D.A. Using genetic algorithms to create multicriteria class intervals for choropleth maps. *Ann. Assoc. Am. Geogr.* **2003**, *93*, 595–623. [CrossRef]

60. Cantarino, I.; Carrion, M.A.; Goerlich, F.; Ibañez, V.M. A ROC analysis-based classification method for landslide susceptibility maps. *Landslides* **2019**, *16*, 265–282. [CrossRef]

61. Baeza, C.; Lantada, N.; Amorim, S. Statistical and spatial analysis of landslide susceptibility maps with different classification systems. *Environ. Earth Sci.* **2016**, *75*. [CrossRef]

62. Süzen, M.L.; Doyuran, V. A comparison of the GIS based landslide susceptibility assessment methods: Multivariate versus bivariate. *Environ. Geol.* **2004**, *45*, 665–679. [CrossRef]

63. Gupta, R.P.; Kanungo, D.P.; Arora, M.K.; Sarkar, S. Approaches for comparative evaluation of raster GIS-based landslide susceptibility zonation maps. *Int. J. Appl. Earth Obs. Geoinf.* **2008**, *10*, 330–341. [CrossRef]

64. Mezaal, M.R.; Pradhan, B. An improved algorithm for identifying shallow and deep-seated landslides in dense tropical forest from airborne laser scanning data. *Catena* **2018**, *167*, 147–159. [CrossRef]