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Geospatial Characterisation of Gravitational and Erosion Risks to Establish Conservation Practices in Vineyards in the Arribes del Duero Natural Park (Spain)

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Abstract: Landslide movements and soil loss due to erosion have increased dramatically, causing numerous human and economic losses. Therefore, it is necessary to delimit these risks in order to prevent and mitigate the effects in natural parks of great value, as is the case of the Arribes del Duero Natural Park. As for landslide movements, they are evaluated by estimating the susceptibility to their occurrence, taking into account the different thematic layers: lithology, geomorphology (slopes, curvature, orientations), hydrogeology and vegetation, weighting each of them using the analytical hierarchy method. Then, by means of map algebra, the cartography of susceptibility to landslides is obtained. On the other hand, the RUSLE equation was used to calculate erosive losses. The results of the gravitational susceptibility are grouped into five classes: very high, high, medium, low and very low, so that the first corresponds to areas of high slope, without vegetation, south facing, with a lithology of quartzites, metapelites and gneisses (canyons, sloping valleys) and, on the contrary, the sectors of lower susceptibility coincide with flat areas, more density of vegetation, north facing, with conglomerates, cobbles, sands and clays, corresponding to erosion surfaces or valley bottoms. In terms of erosion results, the greatest losses are found in areas of steep slopes, with little or no vegetation and with poorly developed soils. Finally, taking into account the cartography of landslide risk, the cartography of potential water erosion and land use, it is possible to determine which conservation practices should be carried out, as well as the land uses that are less susceptible to these movements, highlighting in our study the importance of vineyards in their control.

Keywords: natural risk; soil conservation; vineyards; Arribes del Duero

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1. Introduction

Landslide movements have increased dramatically in recent years, resulting in significant human and economic losses [1,2]. These movements are enhanced by the following factors: geology, geomorphology (taking into account slopes, curvatures and orientations) and land use, the latter being an important factor in the control of such movements. In addition to these factors, there are other factors that occur extraordinarily, such as long-lasting rainfall, earthquakes or more intense human activities [3,4].

Landslides are those ground movements that occur in mass as a consequence of gravity, causing the collapse of slopes with high gradients [5], classified as landslides, avalanches, landslides and flows, both of rocks and soils [6]. One way to understand these movements is to make accurate measurements of vertical and horizontal displacements, which is an essential tool for forecasting future movements and establishing preventive measures [7,8].

There are several methods for susceptibility cartography that use statistical methods and Geographic Information Systems (GIS) tools to determine potentially unstable areas [9–12].

Likewise, another factor to take into account that can affect natural resources is soil loss due to erosion, which has increased drastically in recent years and has become a global problem of great environmental concern [3–5]. Thus, quantifying soil losses is useful for the safe and sustainable development of an area, especially in coordinating effective mitigation measures and strategies [13,14]. To reduce the high losses caused by these movements and erosion processes, critical events and areas must be identified, respectively, as a preventive measure [15–18].

In the specific case of landslides, there are different techniques. One of them performs a comprehensive interpretation of thematic base maps with a statistical treatment, which can be carried out through direct or indirect, deterministic or non-deterministic methods [19,20]. However, nowadays, a wide variety of high-resolution aerial images are available in digital format, which, through GIS, are integrated together with the different thematic layers to result in cartography of susceptibility to these gravitational hazards. The weighting of the thematic factors uses the method of the analytical hierarchy process (AHP), which makes it possible to establish weights according to certain characteristics. This deterministic method can be easily integrated into a GIS, although it can sometimes lead to subjectivity [21–23]. To avoid or reduce this problem, quantitative methods are used that take into account the determination and previous sampling in laboratory analyses [24–26].

For the calculation of soil losses, there are different tools to estimate soil loss empirically, such as the Universal Soil Loss Equation (RUSLE). It is one of the most widely used tools because it is simple and easy to use and, in addition, it allows the integration of different environmental parameters [27,28].

On the other hand, once susceptibility has been assessed, land use and possible conservation practices that reduce the occurrence of these phenomena must be taken into account. One of the land uses is vineyards, whose cultivation on steep slopes requires the construction of terraces or "bancales", which favours hillside stability and reduces erosion, as they act as a brake on runoff [29–31].

Vineyards are one of the world's most important economic sectors, both in the field of agronomy and the environment, and must therefore be preserved, as it is a very important environmental problem affecting several regions. The ecosystem services of vineyards are threatened by different risks associated with unbalanced soil management, such as erosion, loss of organic matter or soil compaction, and reduced vine quality and quantity [32–34]. For this reason, it is interesting to carry out a study of the different risks that may affect vineyards and to determine which conservation practices are the most effective to mitigate possible losses. Moreover, the methodology applied in this study can be extrapolated to other locations with other environmental conditions because it is a simple method that uses data that are available for download.

The objectives of this study are, firstly, to establish and map the gravitational and erosive risks in order to determine the areas most susceptible to these risks in the Arribes del Duero Natural Park; and secondly, the areas in which measures already exist to mitigate these risks and to establish measures in those where they do not exist in order to reduce these risks on the basis of the previous cartography and taking into account land uses, specifically vineyards and their conservation practices.

2. Materials and Methods

The Arribes del Duero Natural Park, located in the west of the provinces of Zamora and Salamanca in Spain, is the study area (Figure 1) and covers an area of 1061 km^2. It has a population of 17,000 inhabitants and 38 municipalities. Climatologically, two climates can be distinguished depending on the area. The valley areas are characterised by very hot and long summers and mild winters, with an average annual temperature of 17.1 °C and rainfall of 500 mm. In the lowland areas, the climate is of an extreme continental type, with average temperatures of 12.2 °C and rainfall of 750 mm [35]. As for the landscape, on the one hand, it is characterised by vertical slopes formed by the canyon (130 m high) of the Duero River, as well as the valleys of its tributaries (Tormes, Uces, Huebra and Águeda) and, on the other, by a peneplain with an undulating surface (with uniform heights of 700–800 m). In terms of vegetation, there are also differences. Thus, on the plain, there are species of the Quercus genus, such as holm oak and cork oak (among others), mixed with other tree species and scrubland, pastures and dry crops such as wheat and barley. On the other hand, on the slopes with agricultural use, there are terraces with vineyards and olive trees, although there are also holm oak and honey oak groves in those areas that cannot be used or have been abandoned due to the difficulty of carrying out conservation practices in areas with steep slopes. Finally, it is important to note that this is one of the areas of the country with large dams and hydroelectric power stations [36,37].

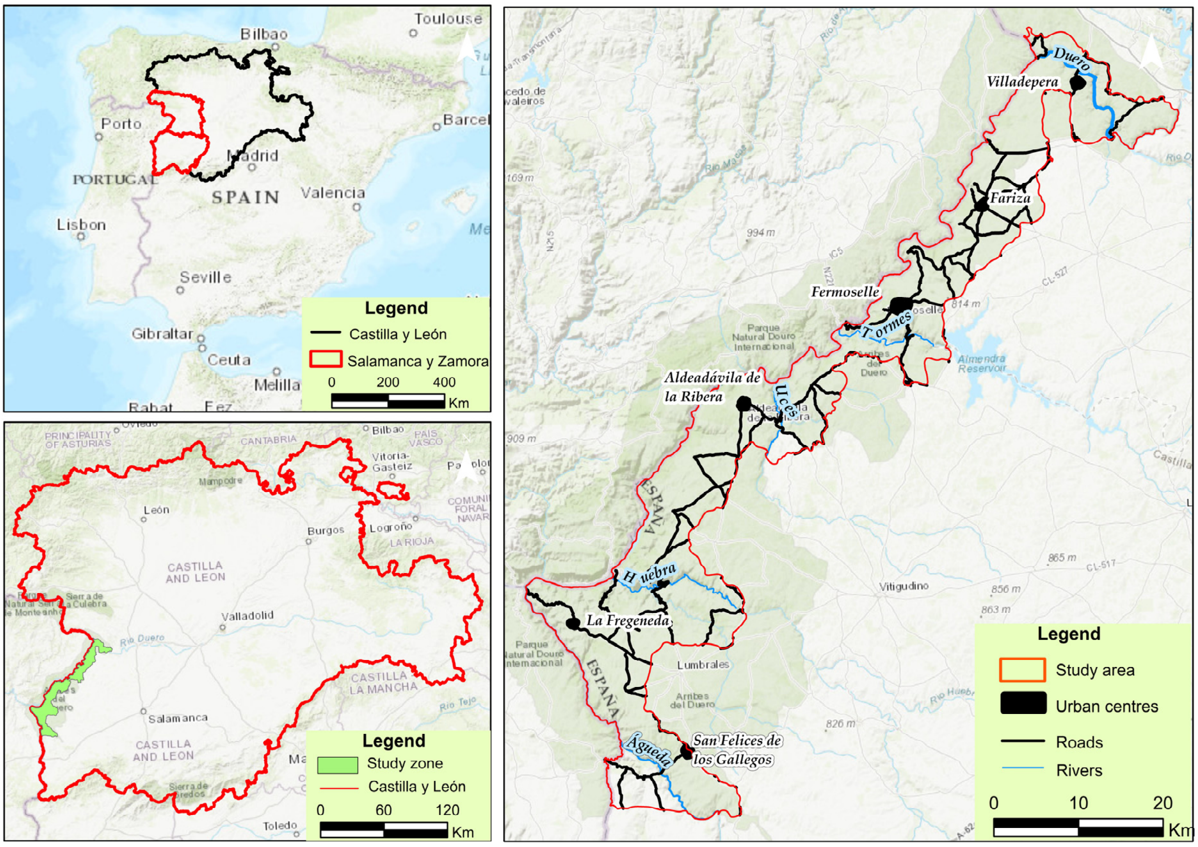

Figure 1. Study area.

The methodology applied in this article for the analysis of gravity and erosion risks is described below (Figure 2):

2.1. Soil Types and Agrological Classes

The study of soils and agrological classes of an area is a key step in the analysis of natural hazards. Knowing the characteristics of soils can help to predict their behaviour in the face of a possible risk. Thus, more developed soils are less susceptible to natural hazards because they have a higher content of clay, organic matter and iron oxides, the latter acting as a bridge between clay and organic matter, which gives the soil a more developed clay–humic complex, protecting the soil from possible erosion or other natural hazards [38]. In addition to knowing the soils, it is also interesting to know their agrological classes, i.e., the suitability of the soils for agricultural development and thus which crops can help to reduce natural hazards.

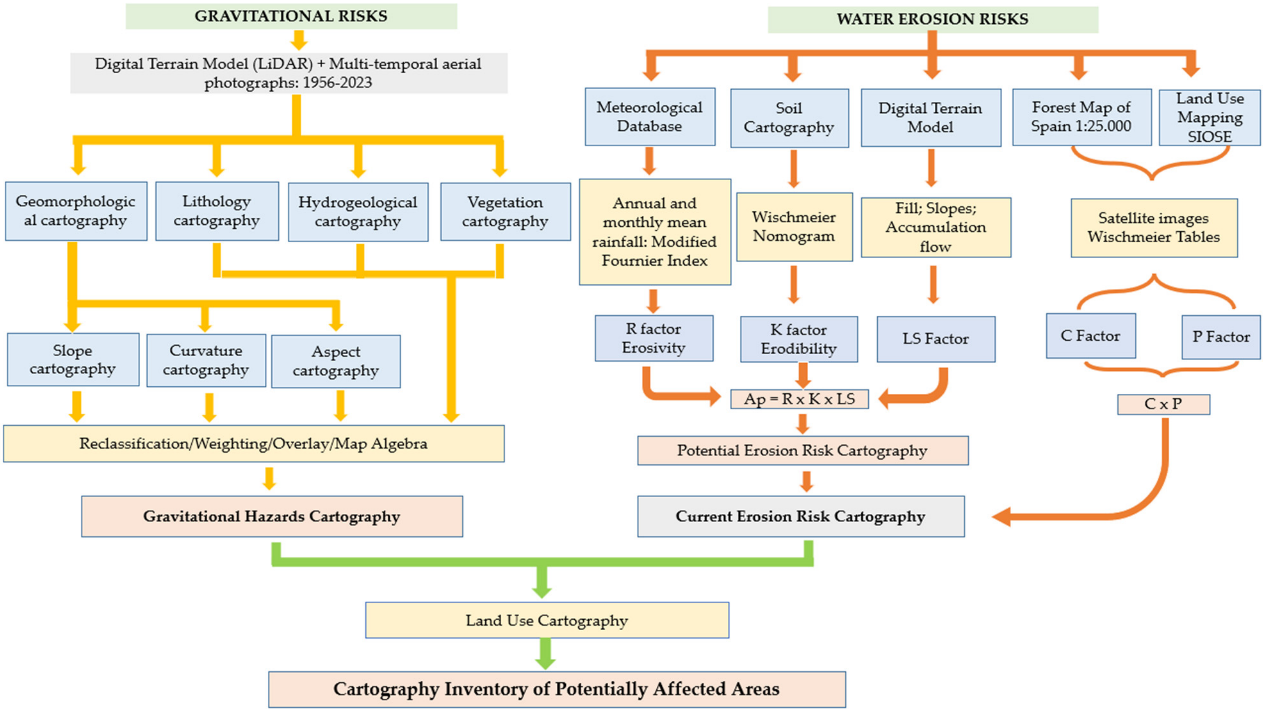

Figure 2. General methodological scheme.

The methodology carried out consists of two phases:

- Soil sampling and analysis: To characterise the study area edaphologically, samples were collected from each horizon of 32 soil profiles, taking into account lithological and geomorphological characteristics. Once the samples were taken, they were air-dried, crushed and sieved with a 2 mm sieve before being subjected to the following analyses: granulometric analysis (Robinson pipette method [39]); organic matter (dichromate oxidation method [40]); cation exchange capacity (ammonium acetate method at pH 7 [39] and pH (potentiometric method). Based on these analyses, the soils are classified and mapped.
- Agrological classes: Once the soils have been classified, their agrological classes are established using the method developed by the Soil Conservation Service of the USA, which establishes eight agrological classes, with I being the best and VIII the worst. This is a categorical system that uses qualitative criteria for the degree of limitation of a parameter according to a specific use. For this purpose, a series of characters are used: slope, soil thickness (cm), stoniness (%), rocks (%), waterlogging, drainage, texture, gravel (%), organic matter (%), pH, degree of base saturation (%), total carbonates (%), salinity, dry months, risk of frost and erosion. The classes are defined on the basis of general criteria, which are simple and easy to adapt to different regions (Table 1). The choice of the agrological class is made on the basis of the maximum limiting factor [41].

Table 1. Evaluation of agrological classes [41].

	Agrological Classes							
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**
Slope (%)	Up soft gently ≤ 6	Up soft gently ≤ 6	Up inclined ≤ 13	Steep ≤ 25	Up softly ≤ 6	Up steep ≤ 55	Up very steep ≤ 80	Up very steep > 80
Floor thickness (cm)	Up Deep ≥ 90	Up to moderate ≥ 60	Up to limited ≥ 40	Up to scarce ≥ 20	Any	Any	Any	Any
Pedregosity (%)	Up to pedreg. ≤ 3	Up to pedreg. ≤ 3	Up to very pedreg. ≤ 15	Up to excessive ≤ 50	Abundant	Up to excessive ≤ 90	Up to excessive ≤ 90	Any > 90
Stones (%)	Up to very bit ≤ 2	Up to very bit ≤ 2	Up to moderates ≤ 10	Up to very rocky ≤ 50	Intense typical	Up to extreme ≤ 90	Up to extreme ≤ 90	Any > 90
Waterlogging	Not: 0 Months	Up to seasonal <3 Months	Up to frequent <6 Months	Up to frequent <6 Months	Intense Very typical	Not permanent <9 Months	Not permanent <9 Months	Any <9 Months
Sewer system	Good or moderate	Somewhat excessive	Imperfect or excessive	Scarce or very scarce	Very escarce	Any	Any	Any
Texture	Balanced	Some unbalanced	Up to unbalanced	Up to unbalanced	Any	Any	Any	Any
Gravel %	Nule or few ≤ 20	Up to moderate ≤ 40	Up to abundant ≤ 60	Up to very abundant ≤ 80%	Any	Any	Any	Any
Organic matter %	Up to abundant ≤ 3	Up to moderate: 2–1	Up to a little bit > 0.5	Up tp scarce < 0.5	Any	Any	Any	Any
pH	Favourable 6.5–7.5	Up to unfavourable 5.6–6.4 y 7.6–8.1	Up to very unfavourable 5.0–5.5 y 8.2–8.3	Up tp very unfavourable 4.5–4.9 y 8.4–8.6	Any	Any	Any	Any
Saturation degree in bases %	Crowded > 75	Crowded > 50	Uncrowded > 15	Any	Any	Any	Any	Any
Total carbonates %	Up to few < 10	Up tp moderate < 20	Up to abundant < 50	Up to very abundant < 70	Any	Any	Any	Any
Salinity (dSm^{-1})	Null or few ≤ 3	Up to weak ≤ 5	Up tp moderate ≤ 8	Up to severe ≤ 16	Any	Any	Any	Any
Dry months	Up to few ≤ 3	Up tp moderate ≤ 5	Up to abundant ≤ 7	Up tp abundant ≤ 9	Arid typical	Any	Any	Any
Frozen risk n.° Months T < 6°	Very escarce ≤ 2	Up to light ≤ 4	Up to moderate ≤ 6	Up to high > 6	Any	Any	Any	Any
Erosion	Null/few ≤ 10	Up to moderate ≤ 20	Up to high ≤ 80	Up to very high ≤ 160	Up to light ≤ 10	Any	Any	Any

2.2. Gravitational Hazards

The study of gravitational risks is carried out by means of susceptibility cartography, which serves to establish the possible incidence of natural processes in a given area. It is also a measure to prevent risk by adopting measures to protect exposed elements when there is no other option [42,43].

The risk analysis of these movements is carried out using non-deterministic methods, by means of the weighting and superimposition of thematic cartographies that serve to identify the conditioning factors for each type of movement: landslides or landslides. From this cartography of passive or conditioning factors, susceptibility maps are obtained [42].

Thus, the methodology followed in this article (Figure 2), takes into account, firstly, fieldwork consisting of direct observation of landslides, as well as consultation of the media and the study and interpretation of aerial photographs, with resolutions of between 90 and 5 metres and, secondly, desk work, to produce each of the cartographies based on the Digital Terrain Model (LiDAR) using ArcGIS 10. 8, all the above information has been obtained from the database of the Technological Agrarian Institute of Castilla y León (ITACYL) and the National Geographic Institute (IGN) [42–47].

(A) Fieldwork. For direct observation of landslide movements in the field, it is necessary to first gather information on historical events: available cartographies, analysis of aerial photographs from different periods and interpretation of orthophotographs [42,43].
(B) Cabinet work. This consists of the analysis of susceptibility to indicate the possibility or special probability of occurrence of an area being affected, giving rise to the susceptibility map. To make this map, the conditioning factors for the occurrence of landslides are taken into account. In this way, a thematic map is made for each conditioning factor and, by means of GIS techniques, it is reclassified into five classes that take into account the behaviour of each one to landslides, using multivariate statistical methods. This reclassification provides numerical values that simplify the initial map without losing any information on these hazards. Finally, to facilitate the interpretation of this map, five classes or degrees of susceptibility are established [48,49].

In terms of statistical analysis, the tool used is the concordance matrix, which makes it possible to study the relationship between qualitative variables, taking into account the combination of the different categories. It is a tool that shows the frequency with which particular combinations of categories occur for each of the variables. It is therefore useful because it records and organises the comparisons made between pairs of items in a set, providing a simple structure for analysis and decision-making based on systematic comparisons.

With regard to thematic factors, it is important to note that they are specific and different according to the territory [49]. In this study, 7 thematic cartographies were considered useful for each factor analysed, based on the Digital Terrain Model (DTM): lithology, geomorphological domains such as slopes, curvature and orientations, hydrogeology and vegetation. Each of the seven cartographies is explained below:

- Geomorphological gravitational susceptibility: The study of geomorphological susceptibility is a useful and indispensable step in the analysis of gravitational risks [42]. In order to draw up this map, geomorphological characteristics have been taken into account, which serves to differentiate a series of units favourable to landslide movements and the development of active processes. Once this cartography has been carried out, each geomorphological unit is reclassified into five susceptibility groups.
- Slope susceptibility: The slope angle is a determining parameter in the existence or not of landslide movements and in the type of movements [42,50]. To make the slope map, the DTM is used, obtaining a one-metre accurate map, using GIS tools. In this way, the slopes are analysed and classified by using multivariate statistical methods, according to the average values of the formations susceptible to sliding.

- Gravitational susceptibility due to curvature: Like the previous ones, morphometry is also one of the most important parameters that control these landslide movements. Thus, concave slopes accumulate more water for a longer period of time, making them more susceptible to the occurrence of these movements. On the other hand, the rocky outcrops, which are the convex slopes, decrease the probability of these landslides, due to the impossibility of water retention [51]. This map was produced from LiDAR, taking into account slope values and orientations to obtain cartography of slopes with a resolution of one metre, and then reclassified by multivariate statistical methods.
- Gravitational susceptibility by orientations: They take into account the influence of the slope di-direction on the sunny and shady sides of the slope, acting as a conditioning factor in the instability of the slope [51]. This map was elaborated, as the previous one, taking into account the Li-DAR and reclassifying according to the susceptibility to landslide.
- Lithological gravity susceptibility: This parameter determines the susceptibility to movement for each type of material. Firstly, physico-mechanical properties are analysed to predict the stability of a slope, under a series of factors that analyse lithological strength [43,52]. This analysis allows us to determine that the rocks that present higher resistance to driving forces are the strongest rocks being less prone to landslides [51]. In this way, for the elaboration of this map, the geological cartographies of the Spanish Geological Mining Institute (IGME) at a scale of 1:50,000 have been taken into account, which, together with the DTM, provides a more detailed map. Then, based on this map, the lithologies are grouped into five degrees of susceptibility.
- Hydrogeological gravity susceptibility: To study this susceptibility, structural and lithological characteristics, the degree of alteration and permeability are taken into account. The loss of stability of the different materials is related to the water table, as a consequence of water reducing shear strength or increasing shear stresses due to soil saturation [43]. The elaboration of this map takes into account, firstly, the lithological cartography and, secondly, the permeability of the different materials, which are then reclassified into five different classes.
- Gravitational susceptibility due to vegetation: The density of vegetation is inversely proportional to landslides [51], i.e., if there is vegetation it will control weathering and erosion, due to the fact that it slows down runoff, playing an important role in the existence or not of slope instability phenomena [49,53]. For the preparation of this map, the existing vegetation maps of the area were taken into account, from which a semi-quantitative assessment was made of the distribution of the vegetation, taking into account its presence or absence and type. Once this has been completed, and together with the reclassification carried out for the calculation of Factor C of erosive risks, they have been reclassified according to the susceptibility values [38].

For the weighting of parameters, the weighted superimposition technique is used, allowing a map to be developed from the superimposition of several raster layers, which are given a weight. First, it is necessary to establish a "Pairwise" concordance evaluation, which relates each pair of parameters, qualifying and quantifying the level of importance of each parameter, assigning values between 1 and 4, according to their predominance [52]. Then, using the analytic hierarchy process (AHP) method (MJA), the weights of each susceptibility parameter are determined [52,54]. This method is a technique used for decision-making involving multiple criteria and alternatives. It is based on the fact that complex decisions can be decomposed into a hierarchical structure comprising general objectives, intermediate criteria and alternatives. In addition, it is possible to obtain relative priorities or weights for the elements at each hierarchical level through a process of comparison, allowing for more informed decision making. To do this, firstly, the overall objectives, intermediate criteria and alternatives are considered in the decision and organised in a hierarchical structure. Secondly, pairs of elements at each hierarchical level are systematically compared, using a relative preference scale that indicates whether one alternative is more favourable than another. This evaluation is carried out to establish relationships of importance and priority between the elements of the analysis. Third, matrices are used to compare the evaluations of the above pairs of elements, reflecting the relative preferences of the elements at a specific level of the hierarchy. Fourth, eigenvectors are obtained from the comparison matrices, which provide relative weights for the above elements, reflecting the relative importance of each. Once the priority information has been obtained, decisions are made, where the best options will be those with the highest weights in the analysis. Finally, once the weighting has been assigned to each parameter, the susceptibility map is generated by means of the weighted superimposition method using ArcGIS 10.8 software. This superimposition process allows the different thematic layers to be combined, taking into account the weights assigned to each one, obtaining a final map that reflects the susceptibility to gravitational movements in the study area.

2.3. Erosive Risks

As in the case of gravitational risks, the methodology used combines field and desk work and also, unlike the previous one, laboratory work, resulting in a series of cartographies of water erosion risk. In the fieldwork, representative samples of the different types of soils are obtained. The laboratory work analyses the previous samples and establishes the necessary parameters to calculate the different factors of the RUSLE in the risk of water erosion. Lastly, in the laboratory work, the data obtained in the field campaigns and the results of the laboratory analyses are analysed by applying different graphic procedures (Wischmeier nomogram, DTM generation...) or empirical procedures (formulas for the calculation of parameters, RUSLE equation...). All of this allows the creation of a database that has been implemented in a GIS (ArcGis 10.8), obtaining different parametric cartographies and the final erosion risk cartographies of the study area. For the quantification of soil losses due to water erosion, two cartographies have been carried out [38,55]:

1. Potential erosion map: this is the susceptibility of an area to erosion under hypothetical natural conditions. To do this, a series of factors of the physical environment that condition erosion processes (mechanical resistance, rainfall, slopes, etc.), are taken into account. Thus, knowing these variables, it is possible to inventory and map the potential erosion units, using erodibility indices (lithofacies and slopes) and erosivity indices (aggressiveness of rainfall):

    - Rainfall erosivity factor -R-: It takes into account the average kinetic energy intensity estimated from monthly and annual average rainfall [56]. In order to be able to use this data, it is also necessary to have a continuous record of rainfall intensity variability, which is available in the database of the Geographic Information System for Agricultural Data (SIGA) [57].

    Thus, for the calculation of this factor, rainfall data from the 35 existing stations with data from more than 20 consecutive years are needed. Then, as a consequence of the dispersion of the stations, interpolation must be carried out using the weighted distance method (IDW) with ArcGis, repeating the same operation for each of the months of the year. Once each raster has been obtained, the modified Fourier index (MFI) is applied (Equation (1)) [58]:

    $$IMF = \Sigma_{i=1}^{12} \frac{p_i^2}{Pt} \tag{1}$$

    P_i: monthly precipitation (mm) and P_t: mean annual precipitation (mm).
    Finally, once all of the above has been calculated, we proceed to obtain the R Factor, for which Equation (2) corresponding to our study area has been used [59]:

    $$R = 2.56 \times IMF^{1.065} \tag{2}$$

    - Soil erodibility factor -K-: Refers to the regional characteristics and the physico-chemical characteristics of the soil. It indicates the probability of a soil to suffer detachment and loss of particles for a specific rainfall. To determine this quantitative value, soil texture, structure, organic matter and permeability are taken into account, using the Wischmeier nomogram [56].

- Topographic factor -LS-: This refers, on the one hand, to the length of the slope (L) and, on the other hand, to the slope (S). Thus, the greater the length, the greater the runoff velocity and, therefore, the greater the erosion [16]. Equation (3) [60] was used to calculate this factor:

$$LS = \left(Flow\ accumulaion \times cell\frac{size}{22.14}\right)^{0.14} \times \left(\frac{sinslope}{0.0896}\right)^{1.3} \quad (3)$$

Flow accumulation: number of flow cells in a given cell; cell size: length of the size of one side of the cells and sin slope: sine of the slope (rad).

Finally, once the above factors have been obtained, they are multiplied by using map algebra to obtain the potential erosion map. Next, the different degrees of erosion are reclassified into smaller intervals by using the following criteria [52,60].

2. Current erosion map: This establishes the current degree or loss of soil in each area, taking into account the conditions existing at present. This is carried out, taking into account the soil forming and protective factors, as well as their spatial distribution, considering the types of crops and native plant masses and conservation practices.
    - Vegetation cover factor -C-: This is responsible for analysing how the presence of vegetation and crops influences the erosive susceptibility of the soil. For this purpose, it takes into account the management of vegetation and crops, established by the Forestry Map of Spain, scale 1:25,000. Finally, once the different plant formations are known, the values established for each of them are taken into account [56] and, in the case of herbaceous formations, the Wischmeier classification has been used [61]
    - Soil conservation practices factor -P-: Indicates the existence of soil conservation practices in land use [62]. In general, it is important to know the potential and real losses taking into account natural factors, i.e., without considering human interventions. For this reason, it is not taken into account, with a Factor P value of 1, which implies that conservation practices that reduce erosion have not been applied [35].

Finally, to obtain the cartography of current erosion risk, the potential erosion map is taken into account. The Universal Soil Loss Equation in its modified version (RUSLE) has been used, which calculates the average annual soil loss taking into account different variations such as climatic variation, relief and the use of conservation practices. The RUSLE is expressed by Equation (4):

$$\mathrm{A} = \mathrm{R} \times \mathrm{K} \times \mathrm{LS} \times \mathrm{C} \times \mathrm{P} \quad (4)$$

A: soil loss ($\mathrm{t} * \mathrm{ha}^{-1} * \mathrm{year}^{-1}$); R: rainfall erosivity; K: soil erodibility; LS: topographic factor; C: land use and management factor; and P: soil conservation practices.

2.4. Identification of Potential Sectors

The identification of places where the probability of occurrence of both erosive and gravitational phenomena is determined by superimposing the cartographies of gravitational susceptibility and current erosion susceptibility and also the updated European digital cartography of land use. In this way, by means of vector tracer spatial analysis of the previous cartographies, it is possible to determine the location of vineyards and mixed vineyard formations associated with olive groves, to identify those located in the areas of greatest risk (gravitational and erosive) and also to check whether there are conservation practices (terraced terraces, ploughing contour lines...) that control these phenomena. This methodology constitutes a rational sustainable planning measure to establish nonstructural measures after knowing where the problem lies and providing a correct solution by means of conservation techniques, thus reducing those high-risk areas where, at present, no type of mitigation has been taken.

3. Results

3.1. Cartography of Soils and Agrological Classes

Once the corresponding analyses have been carried out, the soils are classified according to the results obtained. The table shows the analytical data of a profile of each soil type (Table 2).

Table 2. Soil analyses.

	Horizon	% Sand	% Slime	% Clay	% M.O	pH	C.E.C	% V
Lithic Leptosol	A	66.16	22.31	14.96	1.93	5.16	14.70	37.1
Dystric Leptosol	A	75.15	14.55	10.30	3.03	4.57	9.23	14.1
Eutric Leptosol	A	38.27	50.1	10.92	2.37	3.52	8.84	55.1
Eutric Cambisol	A	72.45	22.34	5.21	3.43	5.20	5.89	50.8
	Bw	70.24	23.11	6.65		4.84	6.54	11.8
Dystric Cambisol	A	81.21	9.65	9.14	1.32	5.42	4.66	24.5
	Bw	67.64	18.59	13.77		5	6.18	12.5
Chromic Cambisol	A	58.22	33.75	8.03	2.87	5.26	11.78	35.3
	AB	62.26	32.03	5.70		5.06	9.09	24.2
	Bw	40.25	41.44	18.31		5.64	17.17	28.7
Eutric Chromic Cambisol	A	59.23	25.13	15.64	2.70	5.78	13.19	45.9
	Bw	46.56	23.77	29.67			20.85	69.0
Dystric Gleisol	A	74.37	18.35	7.28	6.18	4.75	16.90	19.3
	Bw	77.57	16.95	5.48		4.9	10.03	18.4
	C	80.51	13.26	6.23		5.83	9.31	20.5
Gleyic Luvisol	A	77.15	14.29	8.56	1.78	5.99	10.42	32.7
	AB	65.09	23.65	11.26		6	7.33	28.0
	BA	55.86	25.46	18.67		6.03	5.57	66.1
	Btg	36.14	21.75	42.11		6.09	14.53	40.5
Chromic Alisol	A	70.02	20.44	11.45	5.61	5.78	17.01	25.4
	E	64.55	23.07	12.38		5.69	3.43	22.4
	Bt1	31.66	17.07	51.28		5.5	17.44	39.4
	Bt2	44.68	7.00	48.31		5.51	17.26	23.6
	C	58.01	7.19	34.8		5.49	10.63	29.9

According to the degree of development, the soils studied are: Most developed: Chromic Alisols, Chromic Luvisols, Chromic Cambisols and Gleyic Luvisols are found on the oldest surfaces (ravines, glaciers and colluvium); Medium developed: Eutric and Dystric Regosols, Dystric and Eutric Cambisols and Eutric and Dystric Gleysols, the latter located in endorheic areas such as the Navas and less developed: Lithic Leptosols and Dystric Leptosols. All these soils have been mapped (Figure 3A). Thus, the soils that will be most susceptible to natural risk are the less developed soils, i.e., Regosols and Leptosols, which have a higher sand content that acts as erosive agents because they can be displaced by surface runoff. Medium-developed soils such as Cambisols and Gleysols are less susceptible than the above because they have a cambic horizon and a higher clay content. Finally, the least susceptible soils are the more developed Luvisols and Alisols, which have an argic horizon and a higher clay, organic matter and iron oxide content, resulting in a much more stable clay–humic complex.

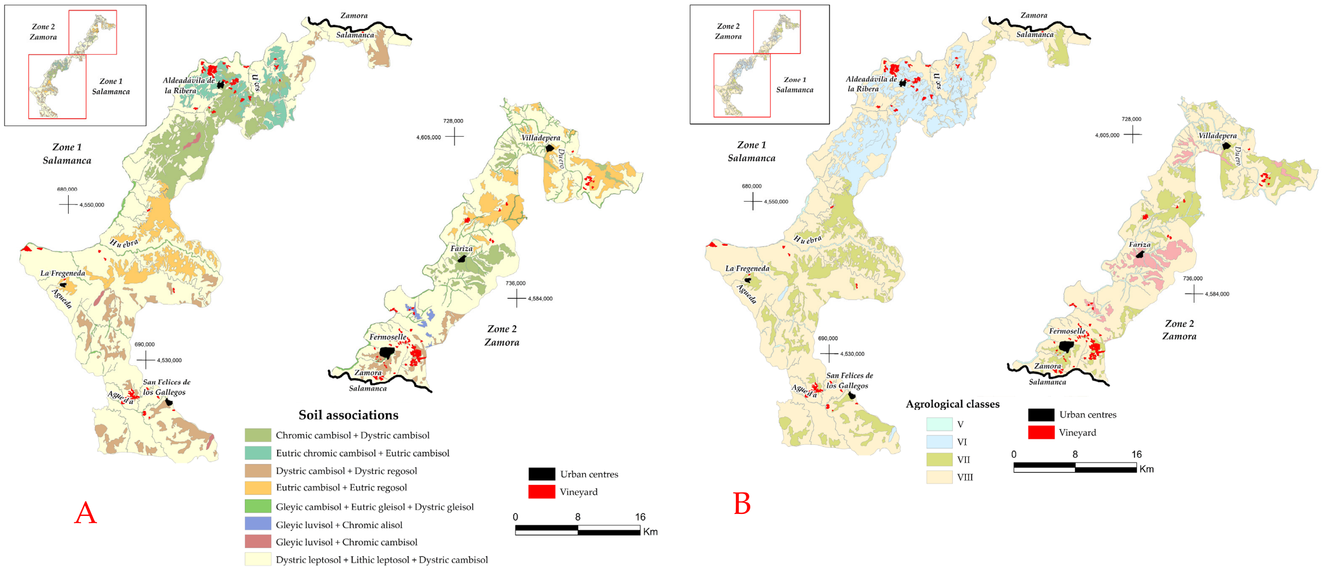

Figure 3. (**A**) Soils cartography; (**B**) Agricultural classes cartography.

Once the soil cartography has been carried out, we proceed to the cartography of agrological classes (Figure 3B). The soils present in Arribes del Duero do not have very valuable agrological classes (Table 3), they are between classes V and VIII. Thus, the soils with the best agrological class are the Dystric and Eutrophic Gleysols, in class V, which are soils that due to their characteristics can be used for pasture or woodland, but not for cultivation due to their waterlogged and stony nature. On the other hand, Luvisols, Alisols, Eutric Chromic Cambisols and Dystric and Eutric Cambisols are class VI, soils suitable for pastures and forests, but with limitations, forestry use is recommended. Eutrophic Regosols and Eutrophic Cambisols, class VII, are soils subject to permanent and severe limitations when used for pasture, located on steep slopes and their use is forestry. Finally, the worst class, VIII, are the Dystric and Lithic Leptosols, they are not suitable either for forestry or pasture, they are stony, eroded soils located on extreme slopes, as in the area of the Duero River canyon.

Table 3. Agrological classes.

	Lithic Leptosol	**Dystric Leptosol**	**Eutric Leptosol**	**Dystric Cambisol**	**Chromic Cambisol**	**Eutric Chromic Cambisol**	**Dystric Gleisol**	**Gleyic Luvisol**	**Chromic Alisol**
Slope (%)	III	III	III	II	II	II	V	II	II
Floor thickness (cm)	VIII	VIII	VII	VI	VI	VI	II	VI	VI
Pedregosity (%)	I	I	I	I	I	I	II	I	I
Stones(%)	I	I	I	I	I	I	II	I	I
Waterlogging	I	I	I	I	I	I	V	I	I
Sewer system	VIII	VIII	VII	VI	VI	VI	V	VI	VI
Texture	III	III	III	III	III	III	III	III	III
Gravel %	VIII	VIII	VII	I	I	I	I	I	I
Organic matter %	III	II	II	I	I	I	V	VI	VI
pH	VIII	VIII	VIII	VI	VI	VI	II	II	II
Saturation degree in bases %	III	III	II	III	III	II	III	III	III
Total carbonates %	VIII	VIII	VII	VI	VI	VI	V	VI	VI
Salinity (dSm^{-1})	VIII	VIII	VII	VI	VI	VI	V	VI	VI
Dry months	III	III	III	III	III	III	III	III	III
Frozen risk	II	II	II	II	II	II	II	II	II
Erosion	IV	IV	IV	III	III	III	III	I	I
Clase agrológica	VIII	VIII	VII	VI	VI	VI	V	VI	VI

3.2. Gravitational Hazards Cartography

First, the susceptibility cartographies for each of the chosen thematic factors are made and reclassified. The reclassification has been carried out in five degrees of susceptibility.

1. Cartography of gravitational risk of slopes: This cartography (Figure 4A) shows that the highest susceptibility which, geomorphologically is the fluvial canyon or embedded valleys among others, is found in the steepest slope areas. In this area, the weathered material is not stable on the slope, which can lead to the detachment of the upper mass when triggering factors such as high rainfall are activated. In the valleys, colluvium or in the domatic forms, they constitute less abrupt areas, with a medium-high slope (20–35°), they are areas with a medium-high susceptibility. In the berrocales or hillocks, with medium slopes which, due to their morphology, concentrate drainage, giving rise to greater or lesser infiltration, pulling up the materials as a result of hydrostatic pressure. Slightly sloping areas, such as dejection cones or glaciers with lower slopes (5 and 15°), have a low susceptibility (slopes between 5 and 15°). Finally, flat areas, such as valley bottoms, Navas, surfaces or terraces, have the lowest susceptibility.
2. Cartography of gravitational risk by aspect: To make this map, the four orientations are taken into account and each of them has a different susceptibility class (Figure 4B): The two highest susceptibilities are sectors with south and west orientations, such as the fluvial canyon of the Duero River and the sloping valleys. On the other hand, the lowest susceptibilities (north and east orientations) are areas with no topographic projections (surface or floodplain areas).
3. Cartography of gravitational risk by curvature: It is possible to distinguish three morphologies; convex, flat and concave. The negative values correspond with convex morphologies, presenting a very high susceptibility. On the other hand, the positive values correspond to the concave and flat slopes, the latter being the one that presents a lesser susceptibility. Likewise, from this map, it is possible to differentiate the valley bottoms, areas of erosion surfaces, terraces and ridges, among others.
4. Cartography of lithological gravitational risk: Cartography (Figure 4C) shows the following values: very high in sectors with quartzites, metapelites and gneises; high in areas with shales and schists; means in leucogranites, biotitic granites and granodiorites; low in porphyry granites and, finally, the lowest are conglomerates, sands and clays.
5. Cartography of geomorphological gravitational risk: In the obtained map it is observed (Figure 4D) that the canyon or valley areas (among others) present the greatest susceptibility, coinciding in turn, with the maximum slopes. For their part, the values of high susceptibility are the coluviones, valleys and domes, while the average susceptibility is characteristic of the berrocals, hills and granitic lehm. As for the low susceptibility they correspond with the projecting cones, the root and the glacis, while the very low susceptibility is flat areas such as valley bottoms, terraces, Navas and surfaces.
6. Hydrogeological gravity hazard mapping: The degrees of susceptibility observed are (Figure 4E): very high correspond to conglomerates, ridges, sands and clays that constitute the Quaternary unit; high correspond to leucogranites and biotitic granites, forming the granitic unit I); average constituted by the granites of granite unit II that are porphyry granites); low with the slates and schists that form the metasedimentary unit and, finally, very low, composed of quartzites and gneises.
7. Cartography of gravitational risk of vegetation: From this map (Figure 4F) it is possible to observe that, the highest susceptibility, corresponds with areas without vegetation, as in the Douro canyon, as a consequence of the existing external geodynamic processes, favouring the instability of the materials of the slope. On the other hand, the high susceptibility is those areas with the presence of seasonal or fallow perennial grasslands, where the probability of occurrence of these movements has decreased with respect to the previous one. The average susceptibility corresponds to sectors

with subarbustive zones as cantuesares, tomillares and jarales or piornales and cambronales, while the low susceptibility corresponds with portesarbustivos as arbustivas formations and roquedos with jaral-heath, larger than the previous ones. Finally, the areas with tree bearing (holm oaks, Alcornocales, dehesas) due to their more developed root system that favours the stability of the slope, fixing and retaining the sediment, constitute the less susceptible areas.

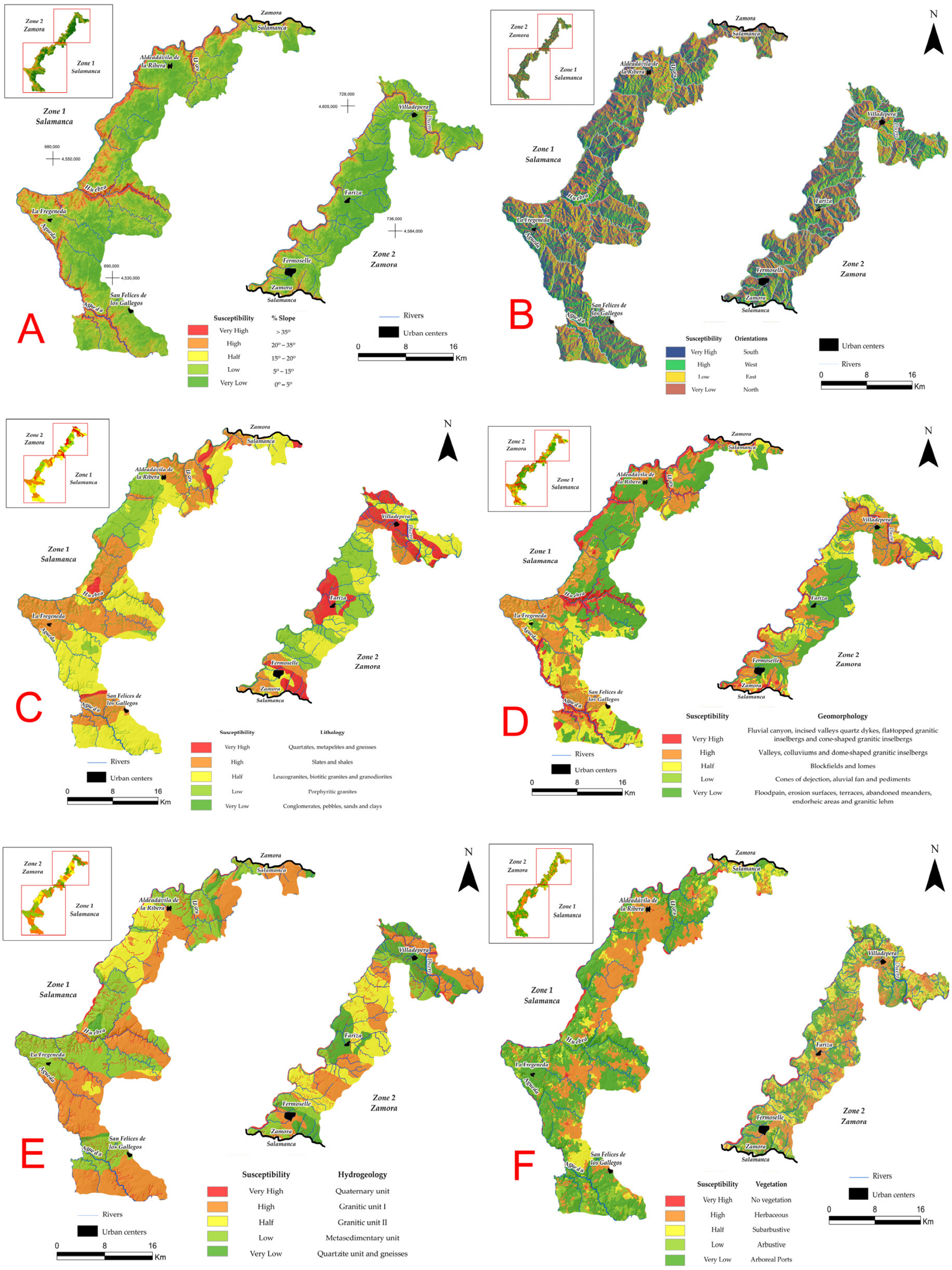

Figure 4. Thematic cartographies: (**A**). Gravitational slope risk; (**B**). Gravitational aspect risk; (**C**). Gravitational lithological risk; (**D**). Gravitational geomorphological risk; (**E**). Gravitational hydrogeological risk; (**F**). Gravitational vegetation risk.

Once each of the previous cartographies has been obtained and reclassified into one of the five degrees of susceptibility; very low (1), low (2), medium (3), high (4) and very high (5), the gravitational susceptibility cartography is obtained (Figure 4). By using map algebra, the final valuation (FV) equation (Equation (5)) has been applied, which multiplies each parameter by its corresponding weighting.

$$V_F = (0.05 \times \text{aspect}) + (0.07 \times \text{hydrogeology}) + (0.10 \times \text{lithology}) + (0.13 \times \text{geomorphology}) + (0.17 \times \text{vegetation}) + + (0.22 \times \text{curvature}) + (0.26 \times \text{slopes}) \quad (5)$$

Taking into account the gravity risk cartography that has been obtained (Figure 5), it is possible to observe that the areas that present the greatest probability of slope movement are: the Douro River canyon and the areas of valleys embedded of the tributaries of greater flow (Águeda, Huebra and Tormes) which, in turn, are areas of high pedigree and with little vegetation. On the other hand, the valleys, colluviums, escarpments and domes, having a smaller slope than the previous ones, are sectors of high gravitational risk, an example of which can be seen in the Huebra and Tormes rivers.

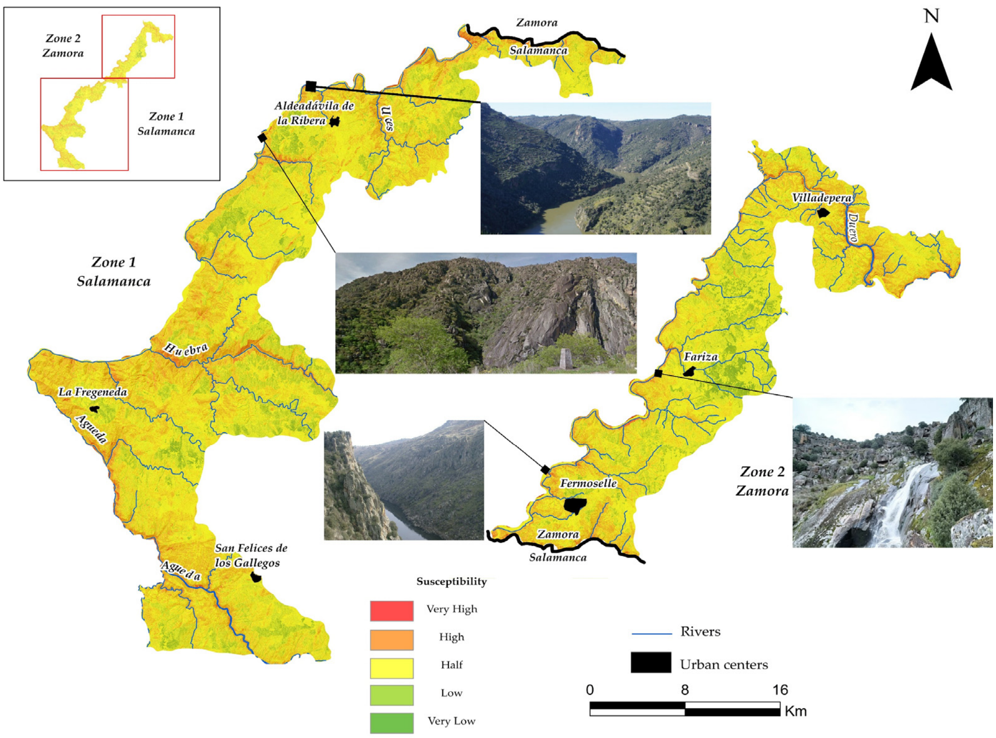

Figure 5. Gravitational erosion cartography.

On the other hand, the zones of berrocals and hills, with a lithology of granodiorites, biotitic granites and leucogranites and a subarbustive vegetation that gives it a greater fixation to the soil with respect to the previous ones, present an average gravitational risk, being the degree of occupation greatest extension.

As for the low gravitational risk zones, they are the root, glacis and deyection cones, with shrubby vegetation and a slight inclination. It is observed in very specific areas, as in the mountains of Cerezal de Peñahorcada.

Finally, the areas of lower gravitational risks are scarce and punctual. They are observed on erosion surfaces, terraces and valley bottoms, with higher-density arboreal vegetation and no slope.

3.3. Water Erosion Cartography

1. Cartography of potential erosion risk: Shows the susceptibility of the area to erosion. It has been carried out by multiplying the R, K, LS factors and by taking into

account the existing conditions. The greatest erosion has values of over 200 Tm/Ha/year and corresponds to the confinement of the Duero, as well as its main tributaries (Tormes, Águeda, Huebra and Uces). In addition, this area has high slopes that favour turbulent movements, giving rise to severe erosive forms such as furrows and gullies. The soils are poorly developed, with higher sand content, such as Leptosols and Regosols [38].

On the other hand, the areas with a moderate and medium erosive level are areas of the plain with values between 10.1 and 50 Tm/Ha/year, with soils with a degree of medium development as the Gleysoles and Cambisols that, unlike the previous ones, have a changing horizon and more clay.

Finally, the erosion levels that can be considered tolerable, that is, up to 10 Tm/Ha/year, are also observed in flat areas, but, unlike the previous ones, the soils are more developed, such as Chromic Cambisols, Gleic Luvisols and Chromic Alisols with a higher content of organic matter and clay and iron oxides in the case of Chromic Cambisols.

2. Current Erosion Risk Cartography: This cartography (Figure 6) is used to indicate the current water erosion risk, taking into account the potential erosion and, in addition, the vegetation cover factor. This factor will provide the soil with some protection depending on its characteristics (height, density, % cover and territorial extension).

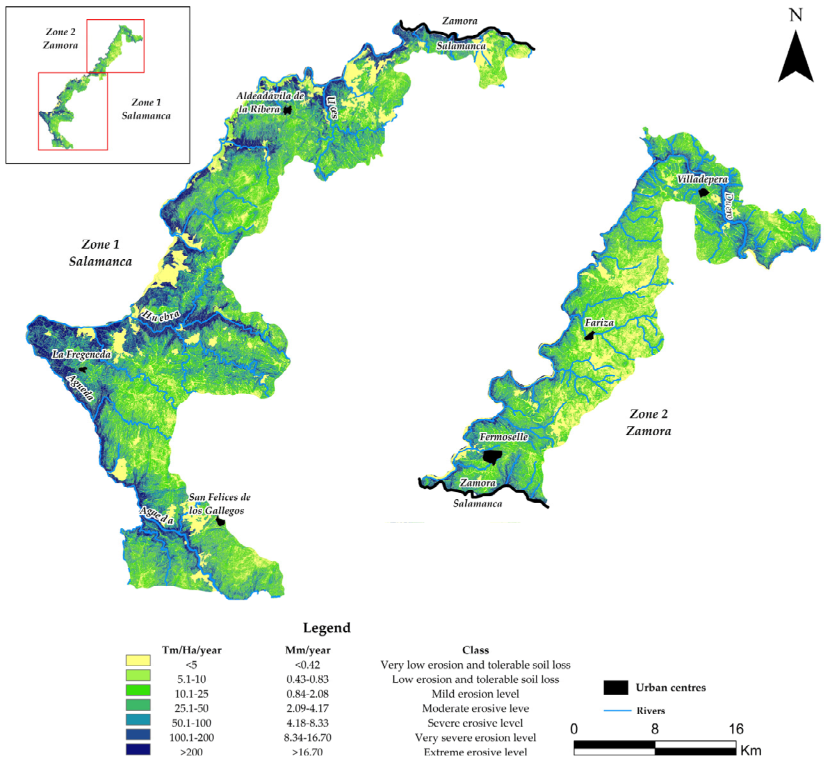

Figure 6. Current erosion cartography.

The greatest erosion, with values between 50.1 and >200 Tm/Ha/year, is observed in areas with steep slopes and scarce vegetation, located in the river beds, especially in the case of the Duero and its most abundant tributaries Tormes, Águeda, Uces and Huebra. The high slopes cause an increase in the speed of surface runoff, making the dragging of the materials most susceptible to erosion, also coinciding with vegetation of low protective power, with low percentages of cover, such as conifers and broad-leaved trees, further accentuating the erosive vulnerability of these soils.

On the other hand, the lowest erosion values, with losses of less than 0.42 mm/year, are observed in the plain areas, i.e., the slope is nil or steep. In contrast, the vegetation has a higher density and herbaceous cover, thus providing greater protection and making this area less vulnerable to erosion.

3.4. Cartography to Identify Potential Conservation Practices

Taking into account the cartography of gravitational risks, the current erosion cartography and land uses, conservation practices can be established to control landslide and erosion, as well as to determine which uses are the most susceptible, thus being able to reduce possible losses. In this way, we have observed that in areas of high gravitational risk and high erosion losses, vineyards and olive groves predominate in areas of high slopes such as the canyon where “bancales” (Figure 7A) and terraces (Figure 7B) have been built in order to reduce the length of the slope and, thus, the speed of runoff. We can also observe vineyards in valley areas and erosion surfaces which, unlike the previous ones, have a lower slope, where contour cultivation has been used as a conservation practice. This type of cultivation and its associated conservation practices mean that the probability of these phenomena occurring is lower. Likewise, in areas where there are no vegetation or conservation practices, landslides and other erosive phenomena are present (Figure 7C,D).

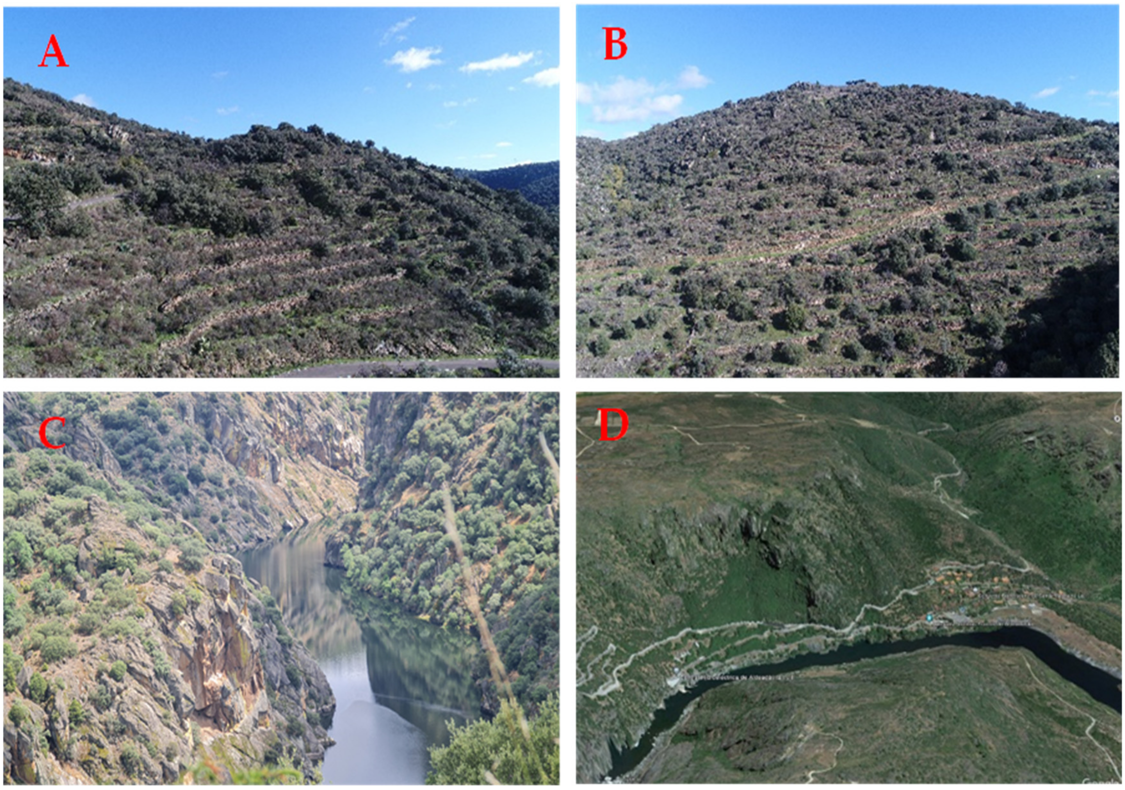

Figure 7. High susceptibility and high erosion areas with conservation practices: (**A**) “Bancales” and vineyards; (**B**) terrace and olive trees. Areas of high susceptibility and high erosion without conservation practices: (**C**) landslides; (**D**) colluvial landslides.

Finally, two cartographies of potential sectors have been drawn up, one based on the gravitational erosion cartography (Figure 8A) obtained and the other on the current water erosion cartography (Figure 8B), on which the areas of vineyards and olive trees have been superimposed, differentiating the places where the risks are currently very high–high and where there are conservation practices and where the risks are very high–high and do not exist. In this way, this cartography can serve as a starting point to establish recommendations for conservation measures and practices to reduce gravitational susceptibility and erosive losses.

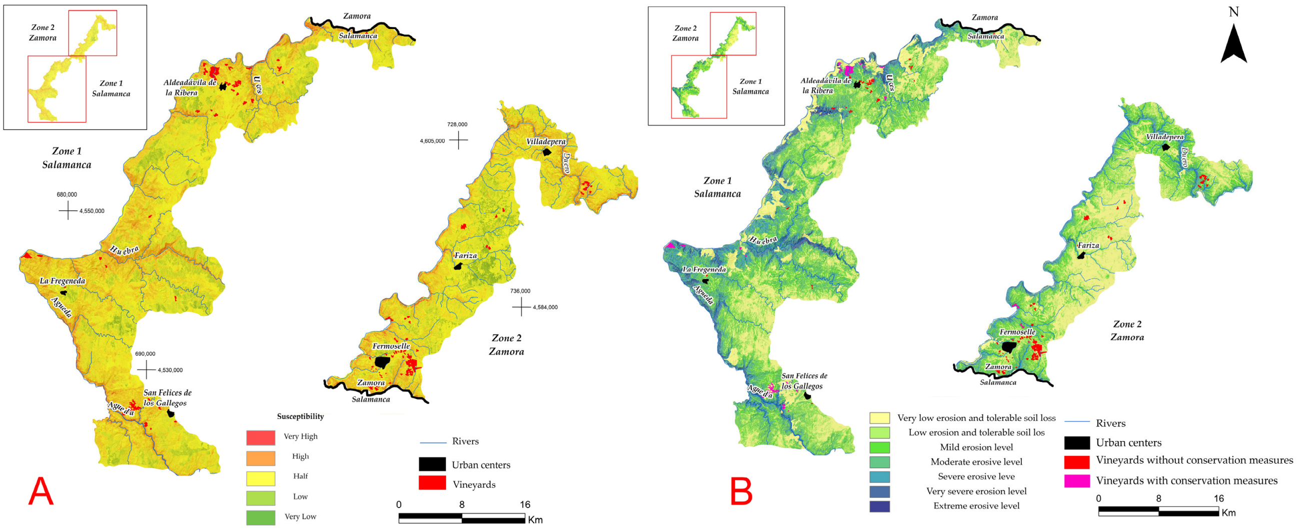

Figure 8. (**A**) Cartography of gravitational processes; (**B**) cartography of potential erosional sectors.

4. Discussion

Gravity and water erosion risk cartography is a crucial tool for assessing and understanding the susceptibility of certain areas to landslides and erosion. Furthermore, these studies are fundamental to implementing appropriate conservation practices and mitigating potential negative impacts on the environment and the population.

Landslides are phenomena that occur gradually, which in turn depend on a series of thematic factors that act directly or indirectly. The selection of these factors takes into account the characteristics of the area and other studies [42–47]. Thus, the factors studied in Arribes del Duero are: geomorphology (slopes, curvature, orientations), lithology, hydrogeology and vegetation.

Water erosion is a process that depends on the action of water as a result of gravity and can be affected by human activities such as deforestation, overexploitation, construction and other physical interventions, causing long-term negative effects, it is necessary to quantify soil losses from this phenomenon in order to ensure sustainable and safe development of an area [63–65].

On the other hand, a solid and reliable methodology must be used to integrate the different data sources with the analysis techniques in order to obtain quality cartographies. In this case, fieldwork has been combined through the on-site observation of events or the sampling of soils (among others) with the cabinet (realization of the different cartographies). In this way, more complete and detailed susceptibility and erosion maps are obtained using GIS techniques.

The methodology used has a series of limitations. On the one hand, it depends on the quality and resolution of the DTMs; high resolutions (of higher quality) entail high processing times, requiring high-powered and high-capacity workstations. In addition, any errors that may exist in these data can affect the final results of the maps. Also, there are problems in the availability of some data, for example, to calculate the R factor of the RUSLE equation, it is more appropriate to use the maximum precipitation in 30 min, but the availability of this data is very small and is not statistically normal, on the other hand, the average monthly precipitation can be contrasted and is available in the State Meteorological Agency (AEMET), that is why this has been used. Another limitation to take into account is the existence of modifications of some of the nomograms used to calculate the K factor, some of the modifications [63] have been contrasted with the original and, in addition, the K values obtained in the national soil inventory at a scale of 1:400,000 have also been reviewed, and it has been verified that the values were similar using any of the nomograms; therefore, in this study, the Wischmeier nomogram has been used, which has been the most widely used, being comparable with the majority of the publications.

Finally, the use of these maps has a number of advantages, providing useful information, on the one hand of the areas most susceptible to landslides and, on the other, to quantify soil losses as a result of water erosion. In addition, with more detailed research, these maps could be validated and supplemented if necessary. It is also possible, by means of land use maps, to check in which areas measures exist to reduce these risks and, also, where they do not exist, to establish them.

5. Conclusions

Nowadays, there are numerous geomatics resources such as GIS and digital spatial data infrastructures such as orthophotos, metric and centimetric DTM models and the use of UAVs, which allow a simple analysis of different natural disasters. Thus, it is possible to assess different risks through the elaboration of cartographies as a preventive measure, such as gravitational susceptibility mapping and current erosion mapping.

The susceptibility cartography makes it possible to establish the sectors in which landslides are most likely to occur, taking into account the different thematic cartographies: slopes, lithology, geomorphology, hydrogeology, aspect, curvature and vegetation. The areas at greatest risk for this type of process have high slopes and scarce vegetation, such as the Duero River canyon. On the other hand, the less susceptible areas correspond to flat areas with higher-density vegetation, such as erosive surfaces or terraces.

Potential erosion mapping allows the calculation and quantification of soil losses caused by water erosion, using RUSLE. Three areas are differentiated: areas with losses exceeding 200 Mt/Ha/year, with large slopes and less developed soils, have an extreme erosive level, and also soil belonging to the worst agrological class, whose agricultural use is very limited; zones with moderate and medium erosive level, with medium development soils, with values between 10.1 and 50 Tm/Ha/year; zones with up to 10 Tm/Ha/year, which are considered as tolerable levels of erosion, are located in flat areas with soils of greater development and vegetation of greater density and herbaceous cover, with an agrological class VI presenting an agricultural use with certain limitations.

Finally, it is important to highlight that superimposition of the cartography of gravitational susceptibility and the cartography of real water erosion with the land uses is a useful and low-cost method that serves to check, in a preventive manner, which conservation practices mitigate landslide movements. Furthermore, it is possible to propose these practices in other places where susceptibility is high, and no type of measure has been carried out.

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