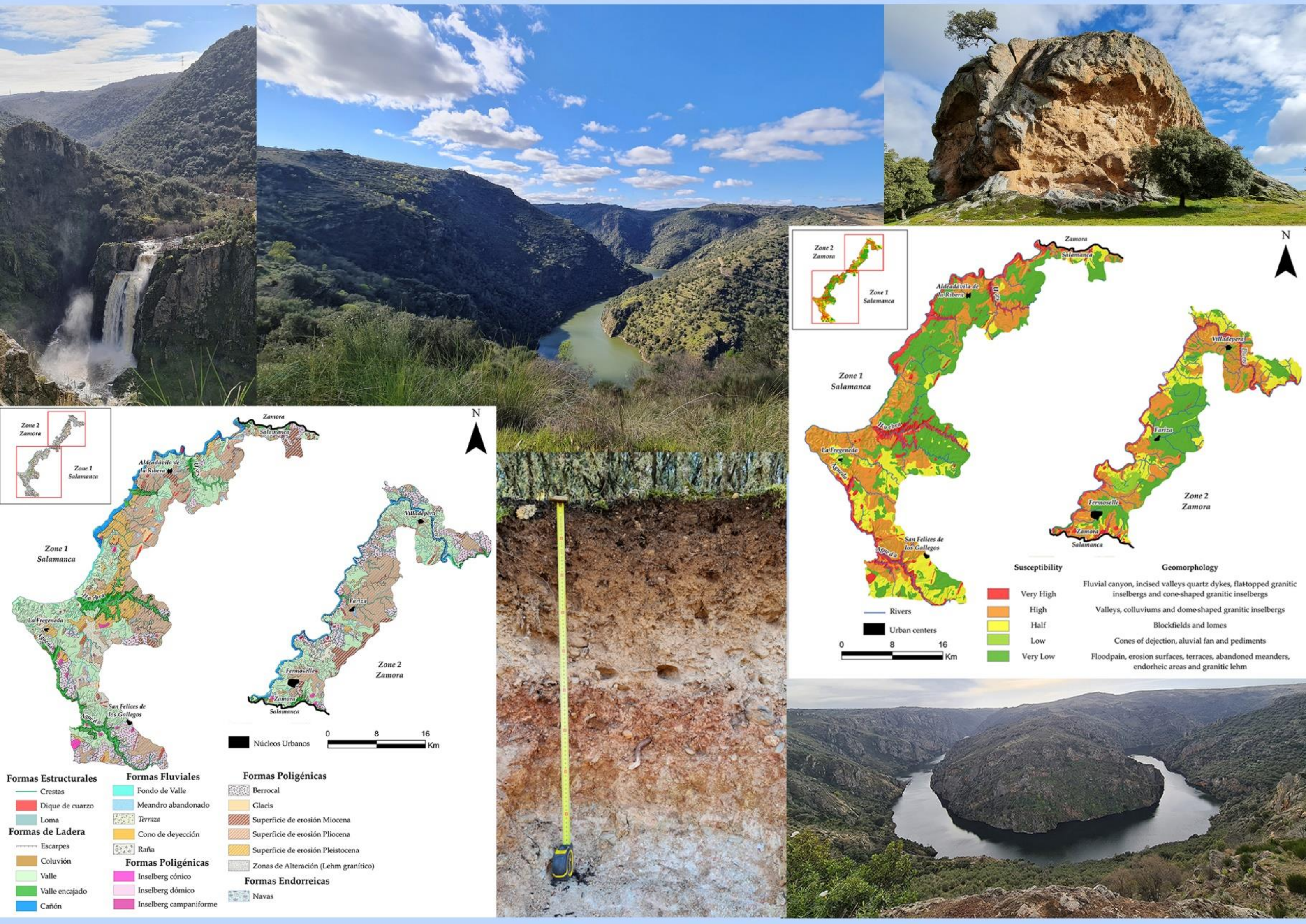
ESTUDIO GEOAMBIENTAL PARA LA PLANIFICACIÓN Y GESTIÓN TERRITORIAL SOSTENIBLE DEL PARQUE NATURAL ARRIBES DEL DUERO



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Departamento de Geología

Área de Geodinámica Externa

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ESTUDIO GEOAMBIENTAL PARA LA PLANIFICACIÓN Y GESTIÓN TERRITORIAL SOSTENIBLE DEL PARQUE NATURAL ARRIBES DEL DUERO

Tesis Doctoral

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CERTIFICAN que:

Dña. Leticia Merchán Hernández ha realizado dentro del programa de doctorado en Geología de la Universidad de Salamanca y, bajo nuestra supervisión, el trabajo para optar al Grado de Doctor en Geología.

"Estudio geoambiental para la planificación y gestión territorial sostenible del Parque Natural Arribes del Duero"

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Dña. Leticia Merchán Hernández.

1 INTRODUCCIÓN Y OBJETIVOS

1.1 Introducción

En los últimos años, los Espacios Naturales Protegidos (ENP) han aumentado un 42% desde la creación de la figura "Área Protegidas" (AP) en 1998 por la Unión Internacional para la Conservación (UICN). Estas áreas son definidas como "una superficie de tierra y/o mar especialmente consagrada a la protección y el mantenimiento de la diversidad biológica, así como de los recursos naturales y los recursos culturales asociados y manejada a través de medios jurídicos u otros medios eficaces". En paralelo con esta figura, se creó otra llamada "Espacio Natural Protegido" (ENP), el cual se define como "un espacio geográfico claramente definido, reconocido, dedicado y gestionado mediante medios legales u otros tipos de medios eficaces para conseguir la conservación a largo plazo de la naturaleza y de sus servicios ecosistémicos y sus valores asociados" (UICN, 2021).

Las áreas de los ENP, desempeñan muchos servicios ambientales como el control y mitigación de los riesgos ambientales y, también, recursos turísticos como la geodiversidad/biodiversidad y paisajes, por este motivo, es necesaria la creación de Planes de gestión. Estos planes requieren políticas de conservación sostenible y racional de los recursos naturales, defendiendo a su vez, los objetivos y la implementación de actuaciones teniendo en cuenta la planificación y gestión, haciendo posible su aprovechamiento en los siguientes años sin que se degraden o agoten.

Para la planificación y gestión de los ENP, es necesario un análisis sistemático y riguroso que disponga de información georreferenciada, facilitando su análisis y manipulación, con el objetivo de conseguir una conservación sostenible eficaz. La elaboración de cartografías geoambientales temáticas básicas constituyen un instrumento y estrategia clave que favorece la integración de proyectos antrópicos en la planificación ambiental. Para ello, se tiene en cuenta, previamente, la evaluación ambiental estratégica y de impactos, mediante la identificación, delimitación y protección de los recursos naturales. Los Sistemas de Información Geográfica (SIG) constituyen una herramienta clave para la organización, manipulación y procesamientos de datos espaciales y, además, para la realización de dichas cartografías. Así mismo, en los últimos años, con el avance de las nuevas tecnologías (cartografías mediante satélite, drones…), los

SIG, tienen un mayor protagonismo en el análisis y la ordenación del territorio, siendo idóneos como herramientas de planificación y gestión de los ENP.

La zona de estudio, Arribes del Duero, fue incluida en el Plan de Espacios Naturales de Protegidos de Castilla y León, creado por la Ley 8/1991, de 10 de mayo, de Espacios Naturales de la Comunidad de Castilla y León (BOE, 158), con la denominación de Arribes del Duero, siendo necesario, según el artículo 22.4 de dicha ley, elaborar un plan de ordenación de los recursos naturales de la zona. Posteriormente, en el año 2002, fue declarado Parque Natural, por la Ley 5/2002, de 11 de abril (BOE, 115), denominado "Parque Natural de Arribes del Duero (Salamanca-Zamora)".

En Arribes del Duero coexisten numerosos atractivos ambientales: geológicos, geomorfológicos, edafológicos y biológicos, además de la belleza de sus paisajes, especialmente en la zona de incisión del Duero y la rica comunidad vegetal y faunística, sobre todo la avifauna, siendo por ello declarada en 1990, Zona de Especial Protección para la Aves (ZEPA), por la Unión Europea.

Arribes del Duero se potencia como un lugar privilegiado para la observación de los diferentes valores ambientales, contando con numerosos miradores distribuidos a lo largo del río Duero, de fácil accesibilidad tanto a pie, con rutas de senderismo, como en coche, en los que, además de poder observar un paisaje singular por el cañón fluvial, también se puede observar su flora y fauna.

La correcta planificación territorial sostenible pasa por identificar y valorar los recursos naturales que definen las áreas de mayor calidad ambiental susceptibles de ser afectadas y a la vez establecer las limitaciones o riesgos, que permitan una ordenación territorial racional y sostenible.

1.2 Área de Estudio

Arribes del Duero es un espacio natural protegido situado en las provincias de Salamanca y Zamora. A lo largo de 120 Km, el río Duero discurre por los materiales rígidos del basamento paleozoico de la Meseta Ibérica, dando lugar a un valle profundo, denominado "arribes", de ahí su nombre, sirviendo a su vez como frontera natural entre España y Portugal (Fig. 1). Este valle profundo, conforma un cañón de hasta 500 m de profundidad, el cual provoca un régimen térmico más suave que ha facilitado el asentamiento de una flora termófila y el desarrollo de olivares y viñedos mediante la construcción de terrazas y bancales en las escarpadas laderas, dando lugar a un paisaje singular. La confluencia de estas peculiaridades, tanto naturales, como paisajísticas y geomorfológicas, justificaron, en 1991, su inclusión en el Plan de Espacios Naturales Protegidos de Castilla y León, siendo declarado como Parque Natural en el año 2002 (BOE, 115). Posteriormente, en el año 2015, fue reconocido por la UNESCO, siendo incluido en la Reserva de la Biosfera Transfronteriza de la Meseta Ibérica, constituyendo uno de los espacios protegidos de mayor extensión de Europa (Marino Alfonso et al., 2021). Además, existen diferentes iniciativas creadas para promocionar lugares de especial interés geológico (Martínez-Graña, 2015; Martínez-Graña et al., 2019) que, a su vez, pueden servir como punto de partida para una posible declaración como Geoparque.

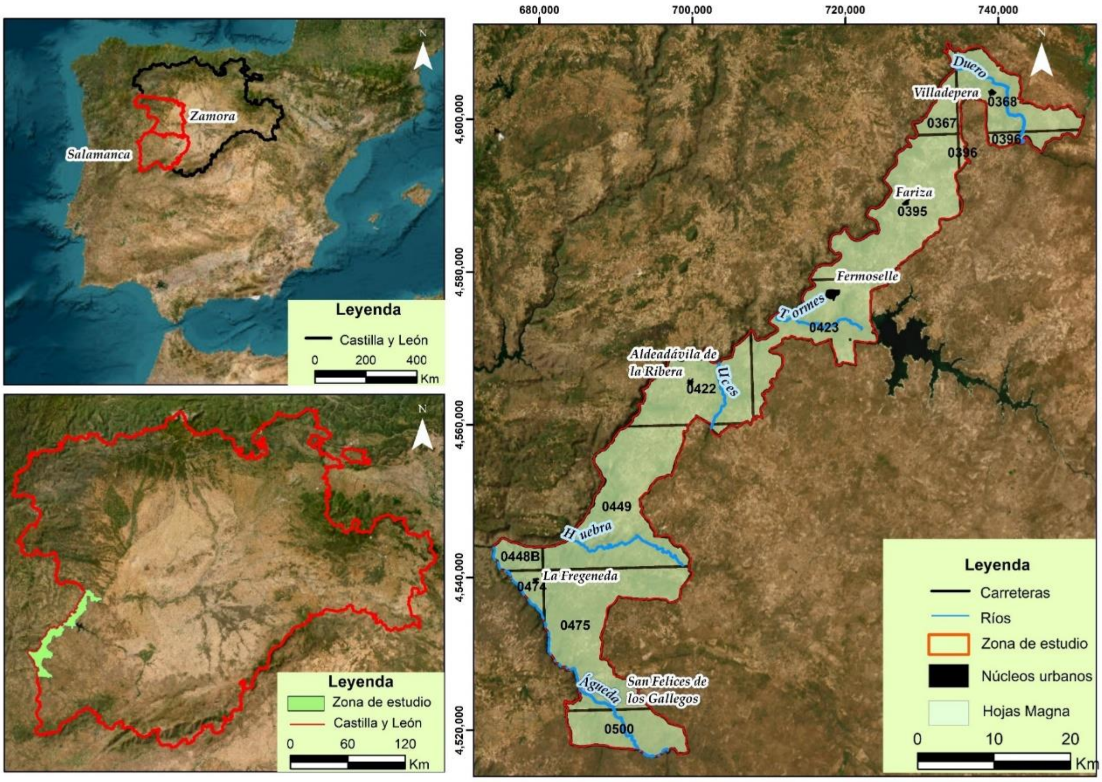

Figura 1.Mapa de situación de la zona de estudio

1.3 Objetivos

El objetivo general de esta tesis es identificar y analizar la calidad ambiental de los recursos ambientales para poder conservar estas singularidades naturales del espacio natural Arribes del Duero y las limitaciones que implican los diversos riesgos geológicos asociados, que puedan servir de base para una planificación y gestión sostenible del territorio, generando una geodatabase temática georeferenciada implementada mediante técnicas SIG.

Los objetivos específicos son:

- Identificar y valorar los puntos de interés geológico y geomorfo-edáfico para poner en valor su singularidad y representatividad favoreciendo el conocimiento integrado del espacio Natural de Arribes del Duero e incluyendo recursos didácticos y geomáticos implementados en plataformas online gratuitas.
- Establecer las unidades de paisaje en base a los componentes y elementos del paisaje, analizando su calidad y fragilidad perceptual, para así determinar el grado de absorción o protección de cada parcela territorial.
- Elaborar la cartografía de calidad para la conservación de forma que se implemente en la fase de anteproyectos, estableciendo aquellos sectores de gran interés como recomendables para su protección.
- Determinar aquellos sectores que presentan gran susceptibilidad al riesgo de erosión hídrica determinando las parcelas territoriales con pérdidas de suelo anuales en base a los parámetros naturales (suelos, vegetación, pendientes…)
- Zonificar los sectores con gran incidencia en procesos gravitacionales que dan lugar a movimientos de ladera.
- Sectorizar desde el punto de vista geotécnico las áreas que presentan ciertos problemas por su peligrosidad natural intrínseca (problemas geomorfológicos, litológicos, hidrológicos y geoténicos).
- Elaborar la cartografía de riesgos integrales para establecer las limitaciones de usos a efectos antrópicos en base a la peligrosidad natural y riesgos asociados.
- Todas las cartografias temáticas permitirán distribuir o validar los diferentes usos del suelo según su capacidad agrícola y de soporte de las diferentes actividades, para, en un futuro, establecer las correspondientes medidas de prevención y mitigación.
- Las propias cartografías constituirán herramientas no estructurales para la correcta, racional y sostenible gestión del territorio, por parte de las administraciones locales y regionales.
- Implementar los Sistemas de Información Geográfica como herramienta para el análisis y la planificación territorial de Espacios Naturales, generando geodatabases interoperables.

2 CONCLUSIONES Y PERSPECTIVAS FUTURAS

Tras el trabajo realizado en el desarrollo de esta tesis se puede concluir que los objetivos establecidos se han cumplido:

En el Parque Natural de Arribes del Duero coexisten numerosos valores ambientales: geológicos, geomorfológicos, edafológicos, conformando paisajes singulares de gran belleza, como el cañón del Duero. Se considera un lugar privilegiado para la observación de estos valores, contando también, con numerosos miradores distribuidos a lo largo del cañón, de fácil acceso, tanto a pie como en coche, en los que, además de poder observar el paisaje, también es posible observar la flora y fauna.

Análisis de la Calidad Ambiental. El estudio del Patrimonio natural (clima, geología, geomorfologia, edafología, vegetación y paisaje) es útil para el análisis de riesgos y, posteriormente, realizar una planificación territorial sostenible.

En cuanto a las características de los materiales geológicos y sus estructuras tectónicas, se han representado en las cartografías geológicas (Cartografía Litológica y Cartografía de fracturas, respectivamente). Estas cartografías han sido una herramienta clave para la elección de los LIGs, para la elaboración de la Cartografía de Unidades Homogéneas del Paisaje, así como para determinar la calidad y fragilidad paisajística y, también, para el análisis de riesgos, para la elaboración de la cartografía de susceptibilidad litológica.

El análisis de las formas del relieve se ha reflejado en la Cartografía Geomorfológica, teniendo en cuenta cartografías históricas, pero utilizando el MDT de 1 metro, para así obtener una cartografía de gran detalle. Constituye una herramienta esencial debido a que está relacionada con los diferentes elementos del medio físico (geología, edafología, etc.), utilizándose en el desarrollo cartográfico posterior (análisis de riesgos), elección de los LIGs y, también, para la elaboración de la Cartografía de Unidades Homogéneas del paisaje y la determinación de la calidad y fragilidad paisajística.

El estudio de la edafología de la zona se realizó teniendo en cuenta el trabajo de campo con la toma de muestras y, también, con cartografías históricas ya realizadas, obteniendo la Cartografía Edafológica y la Cartografía de Clases Agrológicas. También, constituyen una herramienta útil para la elección de los LIGs, como para el análisis de riesgos de erosión hídrica y movimientos de ladera y, además, son de gran utilidad para la asignación de usos de suelo en función de sus aptitudes y funciones ecológicas para la elaboración de futuros planes de Ordenación Territorial.

El "Itinerario Geomorfoedáfico" es útil porque se trata de una herramienta que pone en valor diferentes recursos ambientales (Geológico, Geomorfológico y Edafológico), permitiendo seleccionar aquellos puntos o lugares que presenten diferentes características que sean de interés didáctico, científico y cultural. También, resulta útil porque favorece el conocimiento integrado del territorio, facilitando la planificación y gestión del ENP.

En cuanto al análisis del paisaje, es útil llevar a cabo una caracterización de unidades homogéneas del paisaje para evaluar la incidencia y notoriedad de cada una en el entorno natural y, con ello, establecer la calidad y fragilidad de del paisaje. Además, proporciona localizaciones de las zonas de alta calidad y fragilidad paisajística, que necesitan ser protegidas de las actividades humanas.

Se han diferenciado 12 unidades de paisaje, las cuales han sido cartografiadas e identificadas en el terreno mediante observación directa y análisis de los componentes y elementos de cada unidad perceptual, permitiendo realizar un análisis de la calidad y fragilidad paisajística. El paisaje de este ENP presenta una mayor calidad y fragilidad en las zonas del encajonamiento del Duero, dónde las elevadas pendientes dificultan los asentamientos humanos.

Finalmente, la Cartografía de la Calidad para la Conservación o de Recomendaciones, nos permite determinar los sectores del territorio a proteger. Se observan cuatro zonas en función del grado de conservación: Muy alta, en los dominios del cañón del Duero, en los valles encajados de los ríos más caudalosos y en los sierros, como el de Cerezal de Peñahorcada; Alta, en zonas de valle, como por ejemplo en las cercanías de La Fregeneda; Baja, en zonas de glacis y rañas, como por ejemplo en el término municipal de Aldeadávila de la Ribera, y Muy Baja, en zonas de fondos de valle y en las superficies de erosión más degradadas, como en el sector de Cerezal de Peñahorcada y Mieza.

<u>Análisis de los Riesgos.</u> El análisis de riesgos de erosión hídrica, demuestra que la integración de las técnicas SIG y ecuaciones paramétricas como la RUSLE, realiza un análisis multiparamétrico de forma detallada y exhaustiva. Con esta integración, se ha obtenido un mapa de erosión potencial y otro real, a partir de los cuales se han cuantificado las pérdidas de suelo del ENP, como consecuencia de la erosión hídrica. Esta cartografía de riesgos por erosión hídrica constituye, una medida no estructural de bajo coste, que permite la identificación de las zonas dónde es necesaria y urgente la implantación de prácticas de conservación que mitiguen las pérdidas de suelo.

Se han diferenciado tres zonas en función de su grado erosivo: Zonas con nivel erosivo extremo, con pérdidas superiores a 200 Tm/Ha/año, elevadas pendientes, suelos poco desarrollados como Leptosoles y Regosoles, con bajo contenido en arcilla y materia orgánica y con una vegetación con escaso poder protector, baja densidad y cobertura, como coníferas y frondosas. Zonas con nivel erosivo moderado y medio, con valores entre 10.1 y 50 Tm/Ha/año, que se corresponde a penillanura, con suelos de medio desarrollo como Cambisoles y Gleysoles con un horizonte cámbico y mayor contenido en arcilla que los anteriores, y vegetación con cierto grado de protección. Por último, zonas con niveles tolerables de erosión (hasta 10 Tm/Ha/año), también coincide con penillanura, pero con suelos de mayor desarrollo como Luvisoles, Alisoles y Cambisoles crómicos, con mayor contenido en arcilla, materia orgánica y óxidos de hierro, dando lugar a un complejo arcillo-húmico-férrico desarrollado. En cuanto a la vegetación, aporta una mayor protección, al presentar una mayor densidad y cobertura herbácea, haciendo a esta zona menos vulnerable a la erosión.

El análisis de los movimientos de ladera se ha llevado a cabo mediante la susceptibilidad de los diferentes recursos naturales, utilizando para ello, sus cartografías que han sido simplificadas en función de cinco clases de susceptibilidad. Cada cartografía se ha ponderado y, mediante álgebra de mapas, se ha obtenido la cartografía de susceptibilidad de movimientos de ladera.

Esta cartografía de susceptibilidad es una herramienta útil que permite delimitar las áreas más propensas a deslizamientos y, a su vez, puede servir, como punto de partida, para establecer medidas estructurales y no estructurales para la mitigación y gestión en la planificación territorial y actividades humanas.

Se han diferenciado cinco clases de susceptibilidad: Muy alta: son zonas con muy alta posibilidad de movimiento de ladera, presentan una extensión de 5.1 % y se corresponden al cañón fluvial del Duero, a los valles encajados de los tributarios más caudalosos (Águeda, Huebra y Tormes), como, por ejemplo: deslizamientos coluvionares, reptación de suelos, resaltes graníticos, escarpes de rotura circular, entre otros. Sectores de susceptibilidad alta, es la segunda que más extensión ocupa, con un 18.6%, correspondiéndose con los dominios geomorfológicos de valle, coluviones, escarpes y formas domáticas. Susceptibilidad media propia de berrocales, con una vegetación de tipo subarbustivo y es la que más extensión ocupa con un 65.7%. Susceptibilidad baja, localizada en zonas de ligera inclinación, como glacis, rañas y conos de deyección, además de tener una vegetación de mayor desarrollo, de tipo arbustivo, ocupando una extensión de 10.6%. Susceptibilidad muy baja, se corresponde a zonas llanas como las superficies de erosión, fondos de valle y terrazas con vegetación de mayor densidad, de porte arbóreo, siendo la que menos extensión ocupa, con apenas un 0.04% de la superficie.

Una herramienta útil de bajo coste es la superposición de las cartografías de erosión hídrica real y de susceptibilidad de movimientos de ladera, que permite comprobar, de manera preventiva, qué prácticas de conservación mitigan estos riesgos. Además, también resulta útil, para proponer estas prácticas en otros lugares dónde la susceptibilidad sea alta y no se han llevado a cabo ningún tipo de medida.

En cuanto a la cartografía geotécnica, se ha realizado teniendo en cuenta el análisis detallado de las características litológicas, hidrogeológicas y geomorfológicas, permitiendo establecer una información previa básica a la toma de decisiones. Constituye una herramienta útil porque delimita áreas de recomendaciones y limitaciones de usos en cuanto a actividades constructivas.

Se han obtenido tres áreas geotécnicas que, han sido agrupadas, en función de las características litológicas, hidrogeológicas y geomorfológicas homogéneas: El Área I_1, constituida por rocas graníticas, impermeables y semipermeables, con capacidad de carga alta, presenta unas características geotécnicas favorables a aceptables. El Área I_2 está conformada por gneises que tienen una permeabilidad baja, situados, topográficamente, en zonas estables, con capacidad de carga alta, en términos geotécnicos. Por su parte, el área II, con rocas tipo pizarra, impermeables, con topografía variable (zonas llanas y con pendiente), con alta capacidad de carga. Por último, el Área III, constituida por una serie de afloramientos cuaternarios, de permeabilidad alta y media, con capacidad portante media a baja.

La cartografía de peligrosidad natural complementa a la cartografía geotécnica y se enfoca a una planificación territorial correcta. Se ha realizado teniendo en cuenta las características litológicas, hidrológicas y geotécnicas y, también, las tasas de erosión hídrica real. Permitirá establecer, en el futuro, una cartografía potencial de riesgos para la planificación territorial racional y sostenible.

Se han distinguido 5 tipos de problemas: Problemas de tipo hidrológico, Problemas de tipo litológico y geomorfológico, Problemas de tipo Geomorfológico e hidrológico, Problemas de tipo geomorfológico y litológico, y Problemas de tipo Geotécnico.

Finalmente, la Cartografía Integral de Riesgos establece las Limitaciones de Usos, aportando una información útil para determinar, en fase de anteproyecto, estrategias de planificación y ordenación territorial. Se observan zonas de alto riesgo, tanto erosivo como por movimientos de ladera, concentrados en las zonas

del cañón del Duero y valles encajados de los tributarios más caudalosos. Los problemas litológicos y geomorfológicos, se localizan en zonas con ligera pendiente y materiales impermeables con intensa fracturación, como, por ejemplo, el Sierro de Peñahorcada. Los problemas geomorfológicos e hidrogeológicos, se distribuyen preferentemente en zonas de elevada pendiente, con materiales de naturaleza arcósica y arcillosa, como, por ejemplo, los deslizamientos y desprendimientos observados en valles encajados. Los problemas geomorfológicos y litológicos, se asocian a zonas de pendientes no pronunciadas y materiales con planos de debilidad (estratificación y/o diaclasado).En cuanto a los problemas geotécnicos, se localizan en sectores próximos a Fermoselle, correspondiéndose con materiales sueltos y permeables.
Por último, el uso de las técnicas SIG, ofrece importantes ventajas en la elaboración de las diferentes cartografías y generando una geodatabase digital, interoperable, integrando capas de distintos formatos y de gran precisión, pudiéndose llevar a cabo el análisis comparativo de forma sencilla. Además, la planificación territorial, cuenta con numerosos recursos geomáticos (ortofotos, modelos LiDAR métricos y centimétricos, uso de drones, etc.) que, implementados en SIG, permiten realizar un análisis sencillo de los diferentes procesos naturales.
Todo lo realizado en esta tesis constituye herramientas básicas para llevar a cabo una planificación territorial sostenible. Para ello, como trabajos futuros, que ya están en preparación son:

- ✓ Realizar un análisis de la Geodiversidad del ENP, teniendo en cuenta la diversidad y distribución de los diferentes elementos geológicos. Para ello, se utilizarán las diferentes cartografías de los recursos naturales ya realizadas, la cuales se homogeneizarán, unirán y reclasificarán para, posteriormente, ser convertidas a formato ráster y poder realizar álgebra de mapas, obteniéndose así una Cartografía de Geodiversidad.
- ✓ Realizar una integración de la calidad y la fragilidad paisajística que permita utilizarse como base para alternativas de localización de actividades antrópicas: infraestructuras, de turismo, recreativas y otras que puedan generar impacto visual.
- ✓ Esta Tesis aporta información muy valiosa y de gran interés para los órganos gestores del Espacio Natural de Arribes del Duero, actualizando y realizando las cartografias temáticas de gran detalle y resolución ya que se han aprovechado las técnicas geomaticas y bases de datos de mayor resolución con respecto a las existentes en la elaboración del Plan de

Ordenación de Recursos Naturales -PORN- y el Plan Rector de Uso y Gestión -PRUG-. Además, este espacio natural se integra en el actual proyecto de futuro "Geoparque de las tres sierras y los tres ríos de Salamanca", en referencia a las Sierras de Béjar, Gata y Francia-Quilamas y a los ríos Duero, Tormes y Águeda".

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Article

Geomorphoedaphic Itinerary of Arribes Del Duero (Spain)

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Abstract: In recent years there has been an increasing interest in the Geological Heritage, its evaluation, protection and promotion. The Geomorphological Heritage also interests the scientific community, especially those sectors of great scientific relevance that are characterized by its reliefs. For its part, the soil study provides information about the genesis of the soils and places them as a non-renewable natural resource and highlights the importance of its conservation for future generations. The methodology followed consisted in the valuation of the geological heritage, identifying different places and taking into account the geomorphological and pedological interests, presenting the latter, an innovative character. In this way, a "Geomorphoedaphic" itinerary of the Arribes del Duero Natural Park has been made. This is one of the first steps to its inclusion as a Geopark.

Keywords: geoheritage; geomorphology; soil science; Arribes del Duero

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1. Introduction

At present, there is a renewed interest in the Geological Heritage as well as its evaluation, protection and promotion in various parts of the world [1–5]. Many countries have conducted national geosite inventories to geoconserve them. An example of this is the United Kingdom, with an inventory of geosites since the 1950s and more than 3000 sites, which are currently protected under the figure "Sites of Special Scientific Interest" [6]. As regards Spain, a national inventory was also carried out in the late 1970s. It distinguished 144 geosites of national and international interest [7,8]. Other countries, especially in Europe, carried out geoheritage inventories at national level, although worldwide at present, very few countries have completed a national inventory [9].

First, before defining these Patrimonies, it is interesting to define Geodiversity as "the variety of geological elements (including rocks, minerals, fossils, soils, landforms, formations and geological units and landscapes) present in a territory and which are the product and record of the evolution of the Earth" [10]. For its part, Geological Heritage can be defined as "those natural geological resources (geological formations and structures, geographical features, minerals, rocks, meteorites, fossils and soils) that have scientific, cultural and/or educational value [11]. Likewise, Geomorphological Heritage can be defined as "those places that, in addition to presenting a geomorphological value, also stand out for their historical, cultural, aesthetic and/or socioeconomic values, which deserve to be protected [12]. In this way, it can be concluded that Geodiversity is related to Geological and Geomorphological Heritage but they are different concepts. The first refers to the variety of elements and the second refers to the value of the elements [10]. In recent years, Spanish legislation has significantly strengthened the concepts of Geological Heritage and Geodiversity, as it has included the Places of Geological Interest in the Spanish Inventory of Natural Heritage and Biodiversity. It is important to note that the Geological Heritage has an intrinsic natural value with a social, scientific and landscape significance which also intervene in the management of the territory [13–15].

The study of the Geological and Geomorphological Heritage interests the scientific community, especially those sectors that are characterized by its reliefs and are installed in protected spaces of great scientific relevance [16]. The study of these heritages, which will be based on the elaboration of inventories of adequate size and will identify places of interest, will constitute the most valuable aspect of Geodiversity and will help to analyze their conservation problems and ways of acting accordingly. In this way, all of the above allow to know its didactic and informative potential, as well as being used and disseminated and helping in the definition of strategies, action plans and conservation [3,9,17,18].

Soil science allows to study the genesis of soils, determining the relationship between the soil and the landscape. It is also useful for highlighting the value of soils as a non-renewable natural resource, transmitting to society the importance of their conservation for future generations. Finally, it could be useful to illustrate in a practical way some processes of environmental degradation. An example of this is the "Itinerario edafológico por la provincia de Salamanca: La Armuña-La Dehesa-La Sierra de Francia" [19].

In 2000, a new name emerged for cases where there is a large abundance of relevant geological elements in a region: "geopark". It was not until 2015 when they were officially recognized by UNESCO, which defined geopark as "territories that house unique geological forms of special scientific singular or beauty importance and which represent the evolution of geological history, events and processes that have made exclusive characteristics without ignoring other aspects (ecological, cultural or archaeological) [3,9]. In this way, geoparks seek the promotion of Geological Heritage and sustainable development together, being able to become more than a scientific and educational resource. Last but not least, it serves as an economic resource within the sustainable development strategies of natural parks through geotourism [20–24].

Likewise, the study of geodiversity in a spatial context is of great relevance for geoparks and other protected natural areas to assess geoheritage and manage it, promoting geotourism [25]. In this way, through effective exploitation, benefits can be obtained for scientific, educational and tourism purposes. A suitable approach for such exploitation is the UNESCO Global Geoparks network, as they provide adequate conservation of unique geodiversity localities [26–33]. The fact of the existence of a geopark underlines the importance of the area from a geodiversity point of view, offering also infrastructures for research, education and tourism [34].

In this article, we try to analyze and describe the most representative places in terms of Geological and Geomorphic Heritage in the Arribes del Duero Natural Park (Salamanca-Zamora). In addition, soil science will be taken into account, highlighting the most important soils of these places. In this way, the objective of this work is to carry out a geoenvironmental itinerary, which shows the geological, geomorphological and pedological interests, valuing the geodiversity of said Park, as well as a future inclusion in the list of Geoparks.

2. Materials and Methods

2.1. Study Area

The study area (Figure 1) chosen for this work is the Arribes del Duero Natural Park, located to the west of the provinces of Salamanca and Zamora, on the border with Portugal. It is a protected area of 1061 km^2, consisting of 38 municipalities and a population of about 17,000 inhabitants. Its landscape is characterized by a peninsula with a wavy surface (with uniform heights of about 700–800 m) and the steep slopes that make up the canyons (with heights of 130 m) carved by the river system (Duero, Tormes, Huces, Huebra and Águeda rivers). As for the vegetation, the "peneplain" is a rich mosaic, delimited by walls of stone and pasture, with species of the genus Quercus (holm oak, pyrenean oak, cork oak and gall oak), mixed with other arboreal species (ash trees) and of scrub (woody trees and brooms), pasture and non-irrigated land crops (wheat, barley, rye and vine. On the slopes, located in terraces, olive and almond crops remain, only displaced by pyrenean oaks, holm oaks and junipers, where the agricultural use has been abandoned [35,36]. It is also noteworthy that it is one of the areas with the greatest hydroelectric potential in the Iberian Peninsula. Finally, as far as the climate is concerned, it is characterized by mild winters and long and very warm summers in the valley areas, contrasting with the continental and extreme climate that characterizes the plain [37].

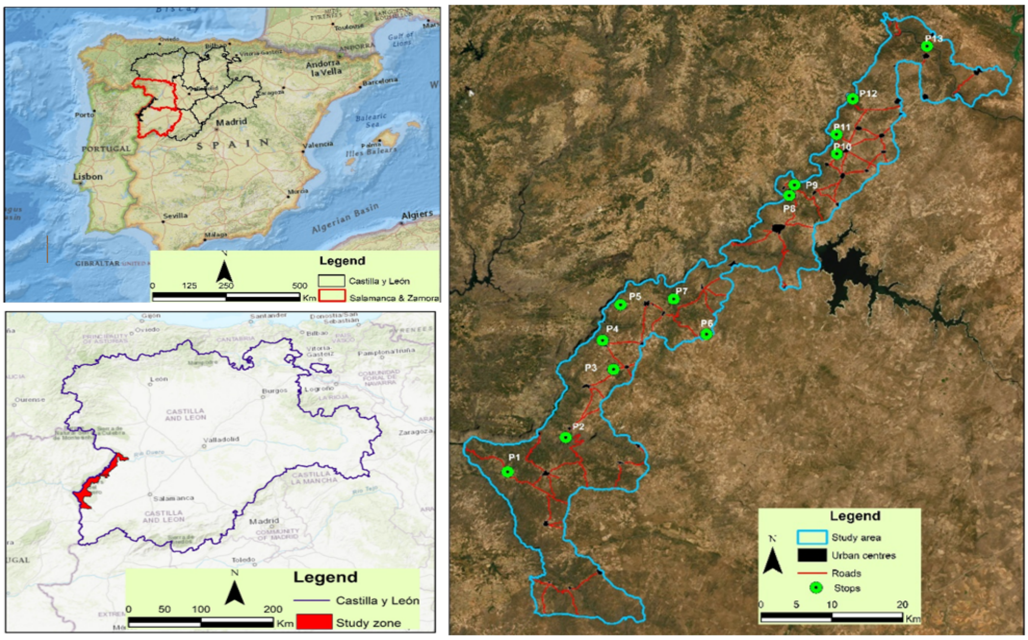

Figure 1. Study area. Source: Author's elaboration.

2.2. Geological Context

From the geological point of view (Figure 2), it is located within the Iberian Massif, specifically in the so-called Central Region, on the W edge of the "Tormes Dome". It is characterized by pre-cambrian and paleozoic formations that were metamorphized, deformed and intruded by plutonic granites during the Variscan Orogen. The materials affected by this orogeny are metasedimentary rocks belonging to the Upper Neoproterozoic or Lower Cambrian of the "Schist-Graywacke Complex", discordant in turn under the Armorican Quartzites of the Lower Ordovician. Likewise, in the lower levels of the metasedimentary series there are abundant fine grained glandular orthognesis. The metamorphism associated with this Orogen transforms the sedimentary sequence into metapelites and gneisses, reaching a partial fusion with the generation and intrusion of anatechnic granites [38–44].

On the other hand, within the granitic rocks and associated rocks, which intrude during the second and third deformation phase, there are a wide variety of types of rocks such as two mica porfhyritic leucogranite, equigranular, from finte to coarse grained. The first are porphyry, of two micas, equigranularity, of fine to coarse grain. The last one, in occasions, can present tourmaline, garnet or cordierite and anatectic origin. Biotic granites are always porphyry and may have muscovite and/or cordierite. As for the intermediate rocks they are related to the previous ones, varying their composition from diorites and monzonites, to tonalites and granodiorites [38,44–46].

The granitic and metamorphic basement is affected in its entirety by alpine faults that determine the subsequent conditioning of the fluvial network. In addition, some of these faults are associated with large quartz dikes that constitute morpho-structural alignments of ridges in the peneplain, what is commonly known as "sierros" [47].

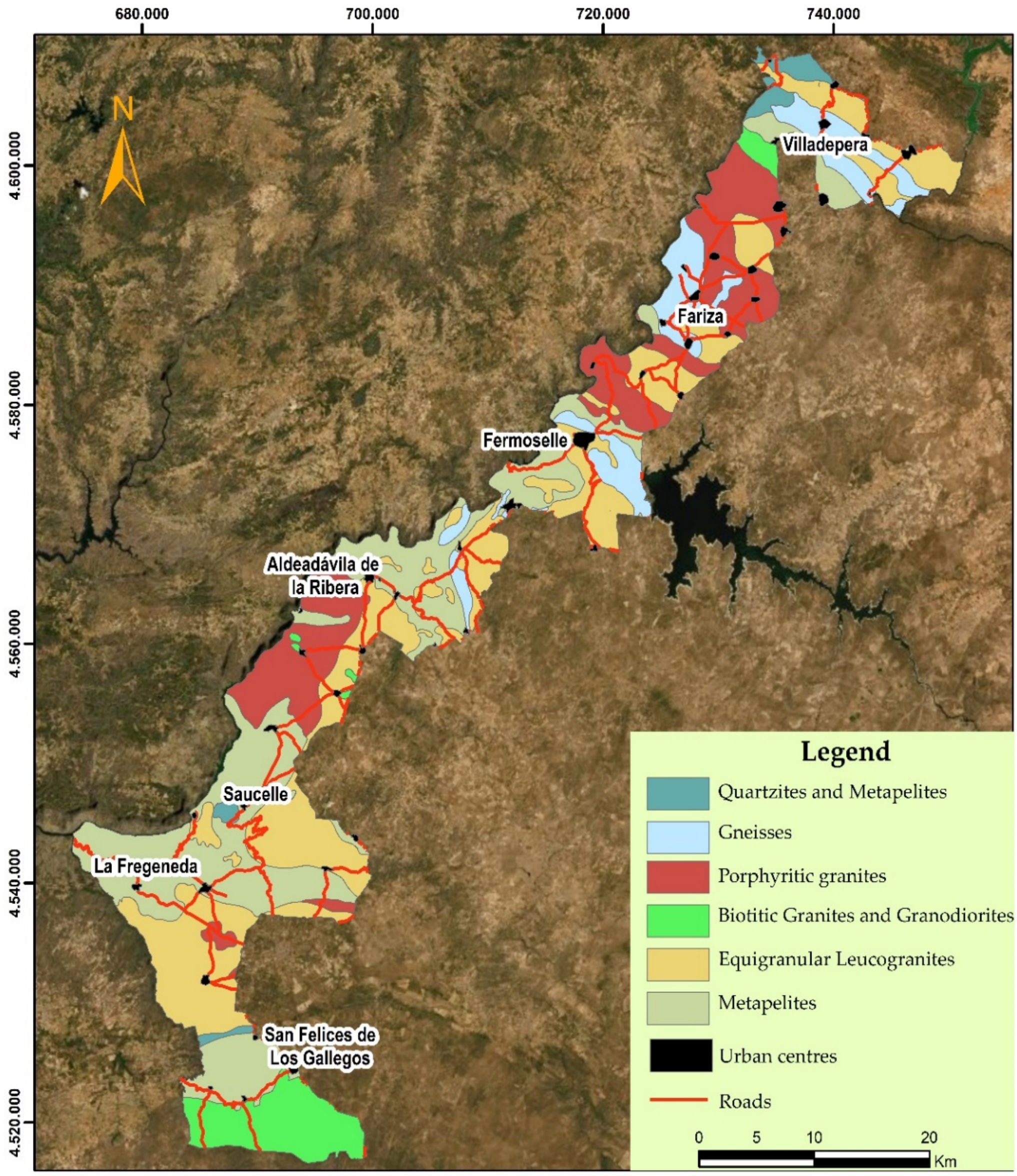

Figure 2. Geologic map. Source: Author's elaboration.

2.3. Geomorphological Context

Most of Arribes del Duero is part of the so-called "Zamorano-Salmantina peneplain". The geomorphological units of the study area (Figure 3), represent a large physiographic unit which, initially, could be defined as a large polygenic erosion surface resulting from the erosion of the Iberian Hercynian Mountain range with warm and humid conditions that dominated during the Mesozoic. In terms of its shape, it is characterized by being hilly or undulating, as a result of erosive processes involving alteration, scouring and fluvial erosion. Although it could be considered as a large surface area, it is actually a multi-cyclic and staggered group, a consequence of a relative lowering of the base level, rejuvenation of the network and reactivation of the landscape [48]. In our study area, six levels or erosional surfaces have been differentiated which are distributed gently staggered towards the west-east, a consequence of the tilting of the plateau towards the Atlantic and, therefore, with ages later than the Oligocene [49].

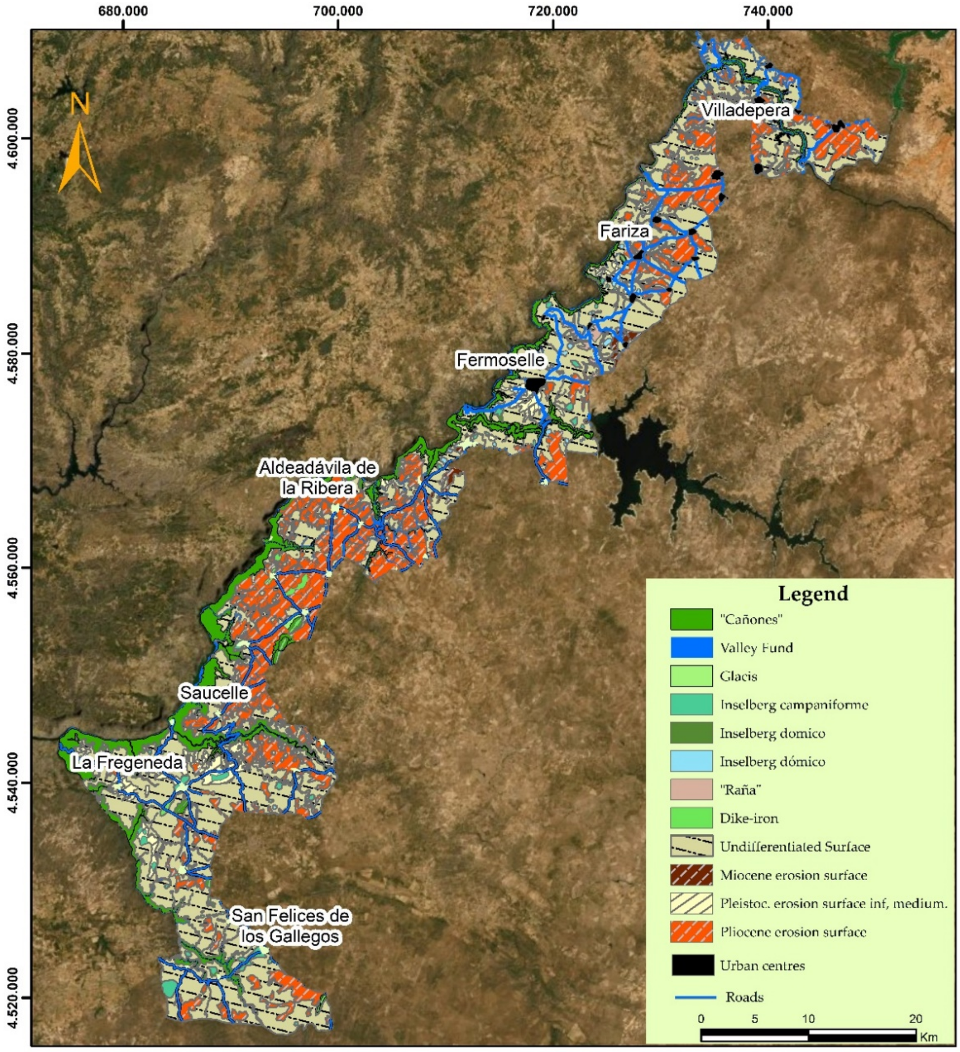

Figure 3. Geomorphological map. Source: Author's elaboration.

In addition to these erosive surfaces, on the monotonous profile of the peneplain, some residual reliefs stand out topographically and in isolation in the form of island hills, known as inselbergs. They are the result of differential erosion emerged from the action, over a long period of time, of several morphogenetic processes typical of subtropical palaeoclimatic conditions [50]. Four types of inselbergs can be distinguished in the study area: linear, flat-topped, conical and domic [49].

Other polygenic forms that can be observed in the area are glacis and block chaos. The former is characterized by a gentle slope (no steeper than 5 degrees), which serves as a link between the riverbeds and the replans of steeper surfaces. Block chaos, on the other hand, are characterized by the concurrence of two or more types of cleavage, generally curved and subvertical, the former giving rise to scree and the latter generating parallelepiped blocks which, by granular disaggregation and flaking, produce the boulders. This form marks some alteration processes that are taking place on the granite and which are currently active, so it is difficult to determine their age [49].

On the other hand, there are other types of forms associated with the presence of water called "fluvial forms". In the area, several types of these forms are distinguished: Alluvial, Terraced, Dejection Cones and Abandoned Meanders. The first is run-up to the valley bottom reservoir of the watercourses, being an area of little development. The terraces are replants formed by alluvial plain deposits that have been hung by the dissection of the drainage network. The dejection cones are elements resulting from the unloading of materials in those places where the morphology of the ground causes the channels of concentrates to be semi-concentrated or dispersed. Also, the abandoned meanders correspond to ancient valleys abandoned by the river or stream due mainly to changes in the longitudinal profile. It is the least common form of the area [49].

Finally, it is possible to observe three other types of forms: hillside, endorheic and anthropic. The first are characteristic of the colluviums found around the inselbergs or other elevated surfaces, i.e., they articulate areas of high slope with other flatter areas. "Navas" are the endorheic forms found in the area. These are characterized by being depressed areas with water retention phenomena, decantations, development of hydromorphism and located in areas of low slope, mainly linked to erosive surfaces. The anthropic forms include dams and quarries [49].

2.4. Edaphological Context

After the fieldwork, the soils were identified (Figure 4), taking into account the geological and geomorphological characteristics of the area, with the following results: Alisols, Chromic Luvisols and Cambisols and Gleyic Luvisols, located on the oldest surfaces, such as colluvium, glacis and "rañas", are the most developed soils in the whole study area; on the most degraded surfaces, less developed soils, Dystric and Eutric Regosols and Dystric and Eutric Cambisols are located. Gleysols have been identified in the endorheic zones (navas), and lastly, Leptosol-type soils with very little development have been described in the canyons. It should be noted that, in the study area, there are no global edaphological works, except for some specific ones.

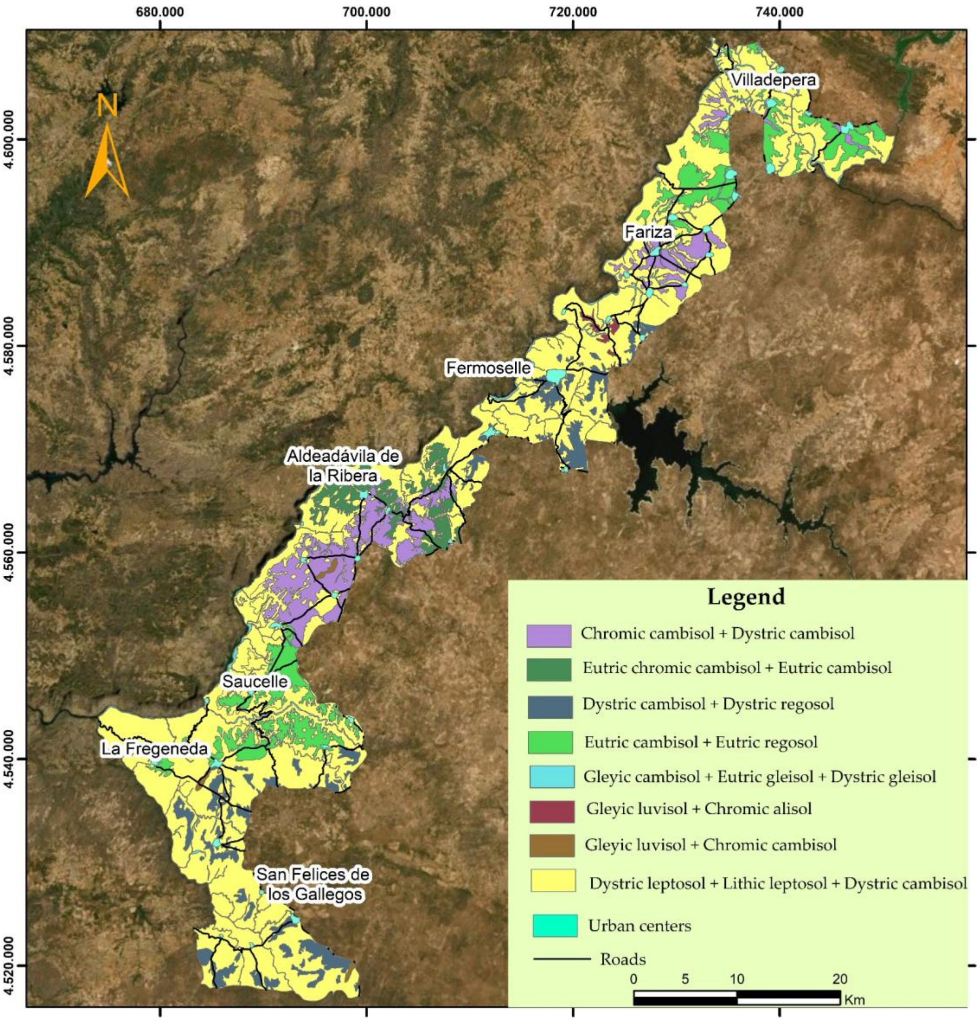

Figure 4. Edaphological map. Source: Author's elaboration.

2.5. Methodology

The methodology followed is based on the quantitative characterisation of the geodiversity, aiming to express, in a more objective way, the special variability of the elements that compose it. In this way, these analyses are based on a set of parameters and numerical indicators that determine the diversity of the geological characteristics of the study area. Although some parameters can be derived from field measurements and remote sensing, most of the quantitative procedures are based on the analysis of diversity maps, as well as the distribution of geodiversity elements of the area in question [8].

Firstly, after an analysis of the existing literature on the area and the field work, the selection of the different points, places or areas of geological importance is carried out, identifying the interest of each element (Geomorphological, Stratigraphical, Mineralogical, Petrological, Palaeontological, Structural or Edaphological) and the type of value it has (scientific, defined by the importance of the element at regional level; didactic, in the case that it clearly shows a process, structure or form of interest; or touristic when it has an impact on the landscape). In addition to these data, the location of the stops, the processes identified and any aspect of interest, the ease/difficulty of didactic and visual interpretation are included, accompanied by illustrative photographs. Geological maps (scale 1:50,000), geomorphological maps (scale 1:50,000) and satellite and Google Earth images of the study area were used to locate the stopes and their accesses. In addition, in the field, each of the stops was georeferenced using a portable GPS and photographs were taken to complement the information described in each one of them.

The assessment of the different points of interest is then carried out, using the methodology used by the Spanish Geological and Mining Institute [51,52]. The evaluation of each point is based on its scientific value (VC), didactic value (VD) and tourist value (VT) and the parameters listed in Table 1. These parameters are based on 4 classes valued from 0 to 4, where the following values are established: intrinsic; intrinsic and use; use and use and protection. In addition to these classes, 18 parameters are valued according to their representativeness, type character, degree of knowledge, state of conservation, conditions of observation, rarity, geological diversity and spectacular nature. These parameters have a relative weight assigned to them (0, 5, 10, 15, 20 or 30). The final result will be the sum of the different parameters for the 3 values obtained for each point.

Table 1. Parameter and Valoration.

Value Class	Parameter	Description	Valoration				
			Parameter Characterisation Aspects	P.	VC	VD	VT
INTRINSEC	Representative (R)	It reports on the quality of the place to illustrate the adequately illustrate the characteristics of the domain	Unhelpful as a model to represent, even partially, a feature or process	0	X30	X5	X0
			Useful as a model to partially represent a feature or process	1	X30	X5	X0
			Useful as a model to represent, in its entirety, a feature or process.	2	X30	X5	X0
			Best known example, at the geological domain level, to represent a feature/process	4	X30	X5	X0
	Type locality character (T)	Informs about the quality of the site as a reference stratigraphic, palaeontological, mineralogical etc.	It does not comply, by default, with the following three premises	0	X10	X5	X0
			Regional reference locality	1	X10	X5	X0
			Internationally used reference locality (metallogenic, petrological, mineralogical, tech-tonic, stratigraphic, etc.), or fossil type locality, or biozones for scientific use.	2	X10	X5	X0
			IUGS-accepted stratotype or IMA type locality	4	X10	X5	X0

Table 1. *Cont.*

Value Class	Parameter	Description	Valoration				
			Parameter Characterisation Aspects	P.	VC	VD	VT
	Degree of scientific knowledge of the site (K)	Indicates that its geological relevance and scientific interest make it the subject of publications and scientific studies.	There are no published works or doctoral theses on the site.	0	X15	X0	X0
			There are published works and/or doctoral theses on the site.	1	X15	X0	X0
			Researched by several scientific teams and the subject of doctoral theses and published works referenced in national scientific journals.	2	X15	X0	X0
			Researched by several scientific teams and subject of doctoral theses and published works referenced in international scientific journals.	4	X15	X0	X0
	Conservation status (C)	Reports the existence of physical deterioration of the trait	Heavily degraded/degraded: the site is practically destroyed or very deteriorated.	0	X10	X5	X0
			Altered: with deterioration that prevents the appreciation of some features of interest.	1	X10	X5	X0
			Favourable with alterations: some deterioration that does not significantly affect the value or interest of the LIG	2	X10	X5	X0
			Favourable: the LIG in question is well preserved, practically intact	4	X10	X5	X0
	Observation conditions (O)	Indicates the extent to which the environment makes it easier or less easy to observe the feature environment to observe the feature	With elements strongly masking the features of interest	0	X10	X5	X5
			With elements masking the LIG and preventing the appreciation of some features of interest	1	X10	X5	X5
			With some elements that do not prevent the LIG from being observed in its entirety	2	X10	X5	X5
			Perfectly observable practically in its entirety with ease	4	X10	X5	X5
	Rarity (A)	Reports on the scarcity of features similar to the one described	There are quite a few similar sites in the region	0	X15	X5	X0
			One of the few known examples at regional level	1	X15	X5	X0
			Only known example at regional level	2	X15	X5	X0
			Only known example at national (or international) level	4	X15	X5	X0
	Diversity (D)	Reports the existence of several types of geological interest on the same site	The LIG only presents the main interest rate.	0	X10	X10	X0
			The LIG has another interest rate, in addition to the principal, not relevant	1	X10	X10	X0
			LIG has 2 interest rates in addition to the principal, or only one but relevant one	2	X10	X10	X0
			The LIG has 3 or more interest rates in addition to the principal, or only two other but relevant ones	4	X10	X10	X0
	Spectacularity or beauty (B)	Reports the visual quality of the feature	Does not meet, by default, all three of the following three conditions	0	X0	X5	X20
			(1) high relief extent, or (2) large watercourses/large sheets of water (or ice), or (3) remarkable chromatic variety. Also fossils and/or colourful minerals	1	X0	X5	X20
			There are 2–3 of the first characteristics. Also spectacular fossils or minerals	2	X0	X5	X20
			Coincidence of the first three characteristics	4	X0	X5	X20

Table 1. *Cont.*

Value Class	Parameter	Description	Valoration				
			Parameter Characterisation Aspects	P.	VC	VD	VT
INTRINSIC AND USE	Didactic Content (CDD)	Indicates whether the feature lends itself more or less easily to teaching or is already used for this purpose.	It does not meet, by default, the following three premises	0	X0	X20	X0
			It illustrates university curricular content	1	X0	X20	X0
			It illustrates curricular content at any level of the education system.	2	X0	X20	X0
			Used regularly in didactic activities at any level of the education system	4	X0	X20	X0
	Disclosure Content (CDV)	Indicates whether the feature lends itself more or less easily to disclosure or is easily disclosed or is already used for this purpose.	By default, it does not comply with the following three premises	0	X0	X0	X15
			It illustrates in a clear and expressive way to groups of a certain cultural level.	1	X0	X0	X15
			It illustrates in a clear and expressive way to groups of any cultural level about the importance or usefulness of Geology.	2	X0	X0	X15
			It is being habitually used for dissemination activities.	4	X0	X0	X15
USE	Potential for tourism and recreational activities (PTR)	Linked to the potential for use. It informs whether the site meets the conditions for leisure activities or whether leisure activities are already taking place.	No tourism or recreation possibilities	0	X0	X0	X5
			Tourist possibilities or recreational activities possible	1	X0	X0	X5
			Tourist possibilities and recreational activities possible	2	X0	X0	X5
			Organised activities are available	4	X0	X0	X5
	Logistics infrastructure (IL)	Informs about the existence of accommodation and restaurants	It does not comply, by default, with the following three premises	0	X0	X15	X5
			Accommodation and restaurant for groups up to 20 persons within 25 km	1	X0	X15	X5
			Accommodation and restaurant for groups of up to 40 persons within 25 km	2	X0	X15	X5
			Accommodation and restaurant for groups of 40 people less than 5 km away	4	X0	X15	X5
	Socio-economic environment (ES)	Reports the existence of several types of geological interest on the same site	The LIG only presents the main interest rate.	0	X10	X10	X0
			The LIG has another interest rate, in addition to the principal, not relevant	1	X10	X10	X0
			LIG has 2 interest rates in addition to the principal, or only oneThe LIG has another interest rate, in addition to the principal, not relevant but relevant one	2	X10	X10	X0
			The LIG has 3 or more interest rates in addition to the principal, or only two other but relevant ones	4	X10	X10	X0
OF USE AND PROTECTION	Association with other elements natural, historical or ethnological heritage (NH)	Whether the site has other non-geological features of interest, which may attract more visitors	No natural or cultural heritage elements within a radius of 5 km	0	X0	X5	X5
			Presence of a single natural or cultural heritage element within a radius of 5 km	1	X0	X5	X5
			Presence of several natural or cultural heritage elements within a radius of 5 km	2	X0	X5	X5
			Presence of several elements of both natural and cultural heritage within a radius of 5 km	4	X0	X5	X5
	Population density (PD)	Linked to potential visits and the increased likelihood of vandalism	Less than 200,000 inhabitants within a radius of 50 km	1	X0	X5	X5
			Between 200,000 and 1,000,000 inhabitants within a radius of 50 km	2	X0	X5	X5
			More than 1,000,000 inhabitants within a radius of 50 km	4	X0	X5	X5
	Accessibility (AC)	It means easier access for visitors, but also easier access for vandalism.	Does not meet, by default, the following three conditions (tarmac road with no parking facilities, footpath or road, TT track, boat, etc.)	0	X0	X10	X10
			Direct access by unpaved track but passable for passenger cars	1	X0	X10	X10
			Direct access by asphalted road with parking for passenger cars	2	X0	X10	X10
			Direct access by asphalted road with parking for coaches	4	X0	X10	X10

Table 1. *Cont.*

Value Class	Parameter	Description	Valoration				
			Parameter Characterisation Aspects	**P.**	**VC**	**VD**	**VT**
	LIG extension (E)	Related to the non-fragility of the element relative to its extent	Metric features (vulnerable to visitation)	0	X0	X5	X15
			Hectometric features (not vulnerable to visitation but sensitive to aggressive anthropogenic activity)	1	X0	X5	X15
			Hectometric features (may suffer some deterioration from human activities)	2	X0	X5	X15
			Kilometric features (difficult to deteriorate by human activities)	4	X0	X5	X15
	Proximity to recreational areas (ZR)	Related to proximity to tourist or recreational areas Linked to potential number of visitors and increased possibility of vandalism	Location more than 5 km from recreational areas (campsites, beaches, etc.)	0	X0	X0	X5
			Site within 5 km and more than 2 km of recreation areas	1	X0	X0	X5
			Site within 2 km and more than 500 m from a recreation area	2	X0	X0	X5
			Site located within 500 m of a recreation area	4	X0	X0	X5

In addition, as a novelty and complement, the soil characteristics of the study area have been taken into account. In this way, by means of field and laboratory work, the characteristic soils have been identified and can be visualised at each of the stops along the route.

3. Results

3.1. Geological, Geomorphological and Soil Itinerary

The studied itinerary consists of 13 stops located in the Arribes del Duero Natural Park, in the provinces of Salamanca and Zamora (Figure 5). In the part of the province of Salamanca, 7 stops have been established: P1: La Fregeneda; P2: Cachón de Camaces and Puente de la Molinera; P3: Sierro de Cerezal del Peñahorcada; P4: Mirador Peña del Águila; P5: Mirador del Fraile; P6: Inselberg de la Peña and P7: Pozo de los Humos. The rest of the stops correspond to the area in Zamora: P8: Meandro del Duero viewpoint; P9: Fornillos cork oak grove; P10: Sierro de Carrascalino; P11: Las Barrancas viewpoint; P12: Peña Gazón and Peña la Galga valley and P13: Requejo bridge.

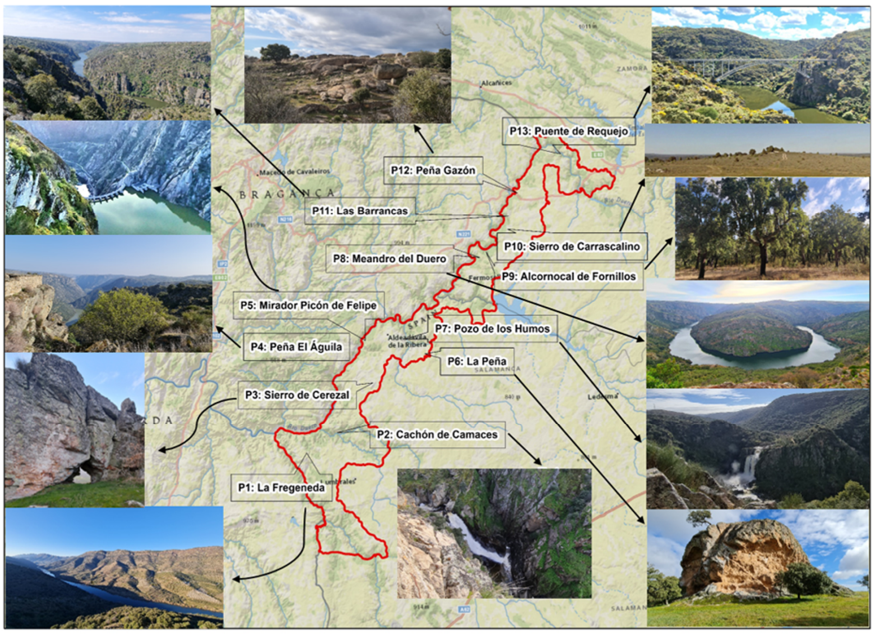

Figure 5. Itinerary of study. Source: Author's elaboration.

The results have been compiled in two tables: Table 2 shows the evaluations of the 13 stops, with the corresponding total value and Table 3 the values of the scientific, educational and touristic interests.

Table 2. Data obtained from the evaluations of each parameter by stops and results of the scientific, educational and cultural interest of each geosite.

Parameter	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
Representativeness	4	2	2	2	2	2	2	4	4	2	2	2	2
Type locality character	2	1	1	1	1	1	1	1	1	1	1	1	1
Degree of scientific knowledge of the site	4	1	1	0	4	4	4	0	1	1	2	2	0
Conservation status	2	4	2	2	4	4	4	2	4	4	4	4	4
Conditions of observation	4	4	4	4	4	4	4	4	4	4	4	4	4
Rarity	2	1	1	1	1	1	1	2	2	1	1	1	1
Diversity	2	2	1	1	2	2	2	1	1	1	2	2	2
Spectacularity or beauty	4	2	1	1	4	2	2	1	2	1	2	1	1
Didactic content	2	2	2	2	4	2	2	4	2	2	2	2	2
Informative content	1	2	2	2	2	2	2	2	2	2	2	2	1
Potential for tourism and recreational activities	4	2	1	2	2	2	2	2	1	2	2	2	2
Logistical infrastructure	2	2	1	2	2	2	4	2	2	2	2	2	2
Socio-economic environment	2	2	4	1	1	1	1	1	2	2	4	2	2
Association with other heritage elements	2	0	2	2	4	2	2	1	0	1	1	1	1
Population density	1	1	1	1	1	1	1	1	1	1	1	1	1
Accessibility	1	4	2	2	2	1	1	2	2	4	2	4	4
Extent of the LIG	1	4	4	4	4	1	2	4	4	4	4	4	4
Proximity to recreational areas	4	2	2	4	2	4	0	1	1	0	2	2	2
Total	**44**	**38**	**34**	**34**	**46**	**38**	**37**	**35**	**36**	**35**	**40**	**39**	**36**

Table 3. Assessment of Scientific, Educational and Tourist Interest.

	Assessment of Scientific, Didactic and Touristic Interest												
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**
Scientific Interest	310	220	190	165	255	255	255	240	285	210	255	235	205
Educational Interest	230	245	215	215	285	200	235	250	230	235	250	245	245
Tourist Interest	205	225	185	235	265	170	175	185	195	200	210	210	195

3.2. Description of the Stops

Stop 1: La Fregeneda (4,539,844.00 m N/679,683.00 m E). This village is located to the northwest of Salamanca, on the border with Portugal, coinciding with the mouth of the Águeda River on the Duero. It is the scientific interest that is of greatest value, standing out above all for its geological characteristics. As for the soil, in this area we can find Cambisols, Leptosols and Regosols (Figure 6E), all of them eutric, due to the large amount of slate existing in the area.It presents a swarm of discordant and concordant pegmatitic dikes rich in lithium associated with hydrothermal quartz seams, which are visible a few kilometers before the entrance to the village (Figure 7A-2). Also, in this area, there is a Tin and Lignite mine "Mina Feli", where you can see these hydrothermal seams cut by the pegmatite dykes belonging to the Grauvacitic Schist complex. There is an impressive viewpoint, "Mirador del Mafeito" (Figure 7A-1) where we can observe the different agricultural uses that can be carried out on the slopes. On the other hand, from this village starts the "Camino del Hierro", a 17 km route where you can enjoy the tunnels and bridges of the old railway line that used to connect Spain and Portugal. This stop has a Scientific Value of 310, a Didactic Value of 230 and a Tourist Value of 205.

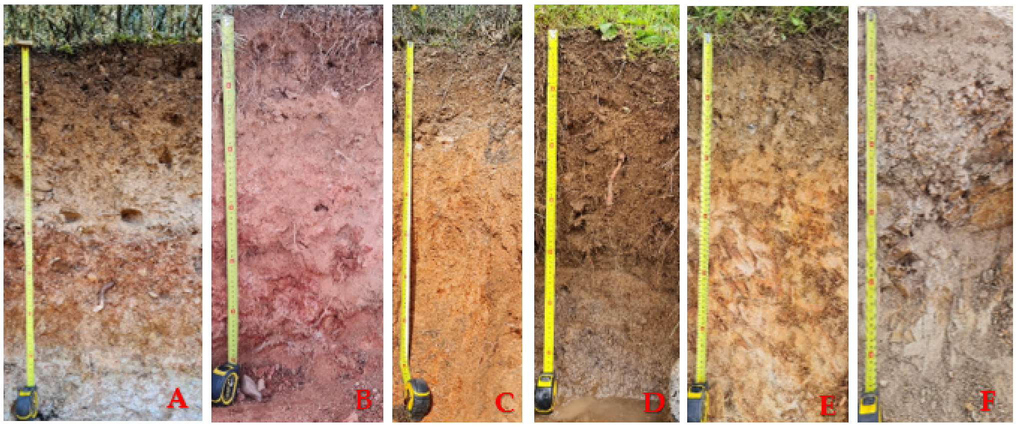

Figure 6. (**A**) Chromic alisol. (**B**) Chromic luvisol. (**C**) Chromic cambisol. (**D**) Dystric gleysol. (**E**) Eutric regosol. (**F**) Lithic leptosol. Source: Author's elaboration.

Figure 7. (**A-1**) View from Mirador Mafeito; (**A-2**) Quartz hydrothermal seams in road cuts. (**B-1**) Cachón del Camaces; (**B-2**) View from Huebra river valley. (**C**) Sierro Cerezal de Peñahorcada; (**D**) View of the Duero from the Peña Águila viewpoint. (**E**) View of Aldeádavila Dam. (**F**) View Inselberg de la Peña. Source: Author's elaboration.

Stop 2: Cachón de Camaces (4,543,441.00 m N/688,967.00 m E). This waterfall is located in the town of Hinojosa de Duero. Its most important interest is didactic. It is both geologically and geomorphologically rich. This waterfall, which belongs to the Camaces river, hence its name, is wedged between two blocks of granite, in order to overcome a great difference in level before flowing a few meters further on into the Huebra river (Figure 7B-1). A few kilometers further on, following the road to Saucelle, is the "Puente de la Molinera", which joins two opposing slopes, crossed by the Huebra river, giving rise to a V-shaped valley (Figure 7B-2). The soils that can be observed here are dystric Cambisols and Regosols. The site has a Scientific Value of 220, a Didactic Value of 245 and a Tourist Value of 225.

Stop 3: Sierro de Cerezal de Peñahorcada (4,552,944,00 m N/694,768,00 m E). This is a very characteristic mountain range of great geological and geomorphological interest. The first thing that can be seen is the hollow that crosses it (Figure 7C), in which the quartz can be seen surrounded by altered granite, but it is also possible to find, a few meters further on, unaltered granite. The origin of these mountain ranges corresponds to the Late Hercynian fracture, which occurred during the Variscan or Hercynian Orogeny during the Carboniferous. In addition, it is also possible to visualize the inverted relief, characterized by the presence of quartzite in the upper part, forming hanging sinforms. As far as the Edaphology is concerned, it is possible to observe a toposequence of soils: Dystric Leptosol, Dystric Cambisol and Gleic Cambisol. In addition, in the vicinity there are "navas", which are depressed areas, flooded by water for a large part of the year, in which the dystric Gleysols (Figure 6D) are characteristic. Regarding the values presented at this stop, they are as follows: Scientific Value: 190; Educational Value: 215 and Tourist Value: 185.

Stop 4: Peña el Águila viewpoint (4,558,996.00 m N/691,388.00 m E). It is located in the municipality of Mieza, from where it is possible to observe different panoramic views of the great Duero River basin, which makes this area so characteristic. It is also possible to see the great difference between the peneplain and the vertical slope called "Arribes" (Figure 7D). These fluvial incisions condition the vegetation due to changes in temperature, altitude and rainfall. On the other hand, it is possible to observe species of vegetation that are of great ecological interest, such as rockroses, broom or lavender, thanks to the fact that, due to the existing geographical limitations, they have slowed down the expansion of agricultural and livestock farming activities. The characteristic soils of this area are mainly chromic Cambisols and dystric Cambisols. The values obtained at this stop are the following ones: Scientific Value: 165; Educational Value: 215 and Tourist Value: 235.

Stop 5: Mirador del Fraile (4,565,660.00 m N/694,802.00 m E). This is an impressive viewpoint overlooking the Aldeadávila dam (Figure 7E). In addition to being able to see the dam, it is possible to observe the fluvial canyon of the Duero, as well as the granite modelling with characteristic shapes such as bell-shaped domes and crags. Therefore, it is an area with very important geological and geomorphological characteristics. With regard to the soil, it is characterized by chromic Cambisols (Figure 6C), dystric Cambisols and dystric Leptosols, the latter in the vicinity of this viewpoint, in the area of the canyons. This stop has a Scientific Value of 255, a Didactic Value of 285 and a Tourist Value of 265.

Stop 6: Inselberg de la Peña (4,561,387.00 m N/708,791.00 m E). Also known as "La Peña de Cadalso", it is a clear example of the residual relief of the Central System, which perfectly characterizes what an inselberg is: isolated granitic forms that stand out from the surface, although it is possible to observe formations of this type in other places in Arribes del Duero (Figure 7F). It is approximately 71 m in diameter and 41 m high. Its geological and geomorphological characteristics are noteworthy. Regarding the former, its lithology corresponds mostly to fine grained leucocratic granites, a rock with pinkish tones without quartz, called episienite. With respect to the latter, its maximum height coincides with that of an ancient surface which has remained as residual relief, the result of the superficial alteration of this sector, thus allowing us to know the existence of surfaces prior to the Duero River being boxed in. On the other hand, on the south face of La Peña, morphologies due to the action of the wind can be observed, generating gnammas and tafonis, which are hollows generated by the atriction of the particles dragged by the wind over the rock. The soils that can be observed are dystric Cambisols and dystric Regosols. The values obtained are as follows: Scientific Value: 255; Educational Value: 200 and Tourist Value: 170.

Stop 7: Pozo de los Humos (4,565,818.00 m N/703,933.00 m E). It can be reached from two places: Masueco, 2.8 km away, and Pereña, 4.5 km away. It is characterized by a waterfall with a constant fall, except in summer. It is possible to observe a wealth of thin granitic sills, alternating with metapelites. As a consequence of this alternation of erosion-resistant granitic materials with more easily eroded metapelite materials, as well as the direction of the orthogonal cleavage in the granite to the course of the Uces River, waterfalls such as this one are formed. In this way, it is a point of great scenic and didactic interest, where it is possible to learn about the factors that have controlled the circulation of water, something that is not usual (Figure 8A). The characteristic soils of this area are the Eutric chromic Cambisols and the Eutric Cambisols. The values obtained at this stop are the following ones: Scientific Value: 255; Educational Value: 235 and Tourist Value: 175.

Figure 8. (**A**) Pozo de los Humos. (**B**) Meander of the Duero. (**C**) Alcornocal de Fornillos. (**D**) View of the Duero from the Mirador de Las Barrancas. (**E**) Sierro de Carrascalino. (**F**) block chaos Peña Gazón. (**G**) Requejo Bridge. Source: Author's elaboration.

Stop 8: Mirador del Meandro del Duero (4,582,453.00 m N/719,721.00 m E). It is located in the town of Pinilla de Fermoselle, from where it is possible to observe the most spectacular and eye-catching meander of all those formed by the Duero as it passes through Arribes (Figure 8B). It stands out, logically, for its geomorphological characteristics, clearly showing the asymmetry of the banks, as well as the development of a semilunar bar, also known as "point-bar". This is a meander in a valley where the geometry of the river coincides with that of the valley. On the other hand, a few kilometres away, we find the Cerro de San Miguel, which represents a domic mountain-island covered with granitic boulders, originated by remaining at a certain distance from the river beds, whose encasement follows the Late Hercynian fracturing [50]. As for the soils, they have very little development, classifying them as dystric Leptosols. The values obtained at this stop are as follows: Scientific Value: 240; Educational Value: 250 and Tourist Value: 185.

Stop 9: Alcornocal de Fornillos (4,545,889.00 m N/723,071.00 m E). Located very close to the village of Fornillos de Fermoselle, although it is not very extensive, it is one of the best examples of cork oak groves in the area (Figure 8C). It is located on a geomorphological formation known as Raña, giving rise to highly developed soils such as the chromic Alisols (Figure 6A) and chromic Luvisols (Figure 6B) that can be found in this area. Thanks to these soils, some species such as the alconorque can develop, therefore, this stop stands out above all, for its edaphological characteristics. Finally, the values obtained are the following ones: Scientific Value: 285; Educational Value: 230 and Tourist Value: 195.

Stop 10: Sierro del Carrascalino (4,588,684.00 m N/726,574.00 m E). It is located between the villages of Fariza and Mámoles. It is one of the most representative lithological outcrops in the area in Zamora. It is characterized by a long, narrow mountain-island associated with a quartz dyke more than 1 km long, standing out against the monotonous profile of the peneplain (Figure 8E). The soils observed in this area are dystric Cambisols. On the other hand, the values obtained at this stop are as follows: Scientific Value: 210; Educational Value: 235 and Tourist Value: 200.

Stop 11: Mirador de las Barrancas (4,591,887.00 m N/726,475.00 m E). It is located in the town of Fariza and is characterized by a granite balcony over the cliffs of the Duero River (Figure 8D). In addition to the view of the river, it is also possible to observe the typical vegetation of this area (rockroses, broom, lavender), as well as the morphology of the place, with the whale backs standing out. In this area, low developed soils such as Dystric Leptosols dominate. As for the values obtained at this stop, they are the following ones: Scientific Value: 255; Educational Value: 250 and Tourist Value: 210.

Stop 12: Peña Gazón and Peña la Galga valley (4,596,238.00 m N/729,215.00 m E). This area is very close to the cross-border town of Miranda de Douro and is another of the most representative places of the Douro river gorge. The streams in this area cross the abrupt change in slope, giving rise to a deep, narrow valley, in which waterfalls, giant marmites, as well as crags and other residual reliefs such as granitic and gneissic nubbins can be observed (Figure 8F). The soils observed are dystric Leptosols, i.e., poorly developed soils, mainly because granites outcrop in most of the surrounding area. This stop has a Scientific Value of 235, a Didactic Value of 245 and a Tourist Value of 210.

Stop 13: Puente de Requejo (4,605,060,00 m N/739,394,00 m E). This viaduct is situated on the northern boundary of the Zamora part of the Natural Park over the Duero River (Figure 8G). From here we can observe part of the interesting metamorphic series characteristic of this area, which is made up of gneisses, schists and quartzites. In addition, this area corresponds to the periclinal end of an antiform, and one of its flanks can be observed from this bridge. In terms of geomorphological interest, this is the area where the canyon begins to be the deepest. In terms of the area's soils, we can observe lithic and dystric Leptosols (Figure 6F). Finally, it is of great interest from the point of view of civil engineering as this bridge, also known as "Puente Pino", forms part of the assets of the National Plan of Industrial Heritage. The values obtained in this stop are as follows: Scientific Value: 205; Educational Value: 245 and Tourist Value: 195.

4. Conclusions

A "Geomorphoedaphic" Itinerary has been created in the Arribes del Duero Natural Park that highlights the characteristics of the Geological and Geomorphoedaphic Heritage, as well as the most representative soils of the area.

The "Geomorphoedaphic" Itinerary consists of 13 stops, that is, 13 Places of Geological Interest, which have been weighted according to their educational, scientific and cultural interest. In addition, the innovative character of the geomorphological and pedological characteristics of each have been taken into account. In this way, in terms of the Geological Heritage, granite rocks, gneisses, metapelites and slates stand out in general terms.

On the other hand, as for the Geomorphology, the most remarkable thing is the box that suffers the Duero River in this area, the Valleys in form of V and reliefs residuals of different types called Inselbergs. Also, the observed soils were, in a dominant way, soils of very little or medium development as Leptosols and Cambisols. On the other hand, exceptionally more developed soils such as Luvisols and Alisols can be found.

Likewise, it also shows different processes of environmental degradation, which can be of anthropic or natural origin. In this way, it is possible to transmit to the Society the importance of preserving all these patrimonies.

In addition, it should be noted that all the stops have a high valuation of the Geological Heritage, concluding that this area, as well as having an important Geological Heritage, also has a Geomorphological Heritage and, to a lesser extent, a Soil Heritage. Thus, this Natural Park could be interesting to be included in the List of Geoparks. For this possible inclusion, a more exhaustive study of the characteristics of the area can be carried out, also taking into account the investigations that have been carried out in the past, as well as the present ones, such as this article. All the information related to this "future geopark" project can be found on its web page: [53].

Finally, the inclusion in the Global Network of Geoparks could constitute an excellent framework to promote the conservation, protection and sustainable use of biodiversity, as well as to promote border relations with our neighbouring country, Portugal, by highlighting the Portuguese part of the Arribes del Duero.

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Article

Geological Heritage in the "Arribes del Duero" Natural Park (Western, Spain): A Case Study of Introducing Educational Information via Augmented Reality and 3D Virtual Itineraries

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Abstract: The concept of geological heritage has been introduced into the protected area of the Arribes del Duero Natural Park, which is west of the Salamanca and Zamora Provinces, Spain for the purpose of developing a guide to places of geological and geomorphological interest, through which geoenvironmental itineraries were developed in order to demonstrate to both the students and tourists, the geological context of the events in the geological history of this natural park. Twelve of the most geologically representative geosites were assessed using 18 quantitative parameters dealing with the scientific, didactic and cultural-tourist interest of each site. The objective of this paper is to describe and analyze the points of interest that are of geoheritage significance and to develop of an inventory that will ultimately facilitate geoconservation and the dissemination of information through educational virtual itineraries that reveal the known geological history of an area. A 3D virtual geological route was created in Google Earth for educational use with superimposed georeferenced cartographies, together with a field guide and an app. The virtual route allows the participants to follow the geological events and the natural history of the park using digital devices in real time with the possibility of observing the relief, the geology and having access to the informative files describing each geosite. Using a field guide, each geosite is complemented with activities, and the participants have the option to evaluate what has been learned. An app makes the itinerary more interactive. These georesources allow a teaching–learning process where the student is an active part of the development and creation of the contents using technologies that provide an entertaining and didactic learning experience, and this involves working as a team and interacting with social networks, thus, potentially influencing the attitudes and skills development that are involved in geoconservation as an element for its sustainable development. The identification of geological heritage currently constitutes a great resource to promote the sustainable development of it and employment in very depopulated rural areas.

Keywords: geoheritage; geoeducation; augmented reality; 3D virtual tour

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1. Introduction

The Arribes del Duero Natural Park (west of the Salamanca and Zamora Provinces, Spain) is a 1061 km^2 large protected area which includes 37 municipalities and a population of about 17,000 inhabitants. The area has great geological and geomorphological values [1]. From a flat surface (the so-called penillanura salmantino-zamorana) of a uniform altitude of about 700–800 m (due to the deep canyons (arribes) that have been carved by the fluvial system (Duero, Tormes, Huces, Huebra and Águeda Rivers)), one descends to about 130 m. Consequently, this border area between Spain and Portugal is one of the areas with the greatest hydroelectric potential of the Iberian peninsula. To add to the topographical environment is that of the vegetation. The vegetation is very different in the "peneplain" with respect to the Arribes due to its climatic conditions. In addition to the riparian galleries and the anthropic action in the terraces where the slopes are high and there are processes of deforestation and erosion, the Mediterranean crops that are produced are usually unfit for this latitude, and there is an unusual thermophilic vegetation assemblage.

This work describes the 12 representative geosites for their rich geological heritage. The known geological information of the area is completed with the study of the geomorphological aspects which are characteristic of the area. Thus, we developed a guide of the places of geological-geomorphological interest, through which the geoenvironmental itineraries can be completed that identify the most representative geological and landscape interests and to facilitate the learning by the main students and tourists of the contexts and events in the geological history of this Natural Park. The area of the Natural Park that belongs to the province of Salamanca is included in the UNESCO World Geopark project [1–4] (https://geo3sr.usal.es/ accessed on 1 august 2022). Geoparks are a recognized model that promotes sustainable development in areas that contain sites of geological heritage (geoheritage) of international significance and promotes geoconservation and geotourism [5,6].

The objective of this paper, therefore, is to analyze points of interest in terms of their geoheritage significance through the development of an inventory that will facilitate geoconservation and the dissemination of information through virtual educational itineraries that reveal the known geological history of the area. Augmented reality is used in order to provide the digital content of the geological heritage in geoapps and virtual flights in real time using smartphones, tablets, etc. Given the general absence of specific geological information on geoheritage values, only the best geosites in the study area have been selected. In this study, we identify the best sites to assess their geoheritage values and at the same time, we advocate for their protection and conservation once the values of them are known.

The educational value of geological heritage of the geosites were analyzed at different educational levels, as well as this, we updated the educational methods using new technologies such as AR and 3D virtual itineraries [2,7–11].

Using geomatic tools, the digital information was compiled from different thematic layers. Photographs, diagrams and descriptive cards were then incorporated to produce the didactic resources. By interacting with the digital information using the free Google Earth platform, 3D virtual "flights", which can be followed in real time, were established and implemented in different formats (mpeg, avi, wma, etc.) that are reproducible in different multimedia systems, thereby increasing the possibility of educational and tourism use by broad sectors of the population.

2. Geological Context

The Arribes del Duero Natural Park is located on the western edge of the "Domo del Tormes", which is an internal orogenic area of the Iberian Massif that is characterized by the development of high-grade plutono-metamorphic complexes. The materials that were affected by these orogenic events are the metasedimentary rocks of the Upper Neoproterozoic or Lower Cambrian age from the "Grauvachian Schist Complex", which are discordant under the Lower Ordovician quartzites (Armorican quartzites). In the lower levels of the metasedimentary series, abundant glandular and fine-grained orthogneiss appear that are of pre-Variscal age [12–14] (Figure 1).

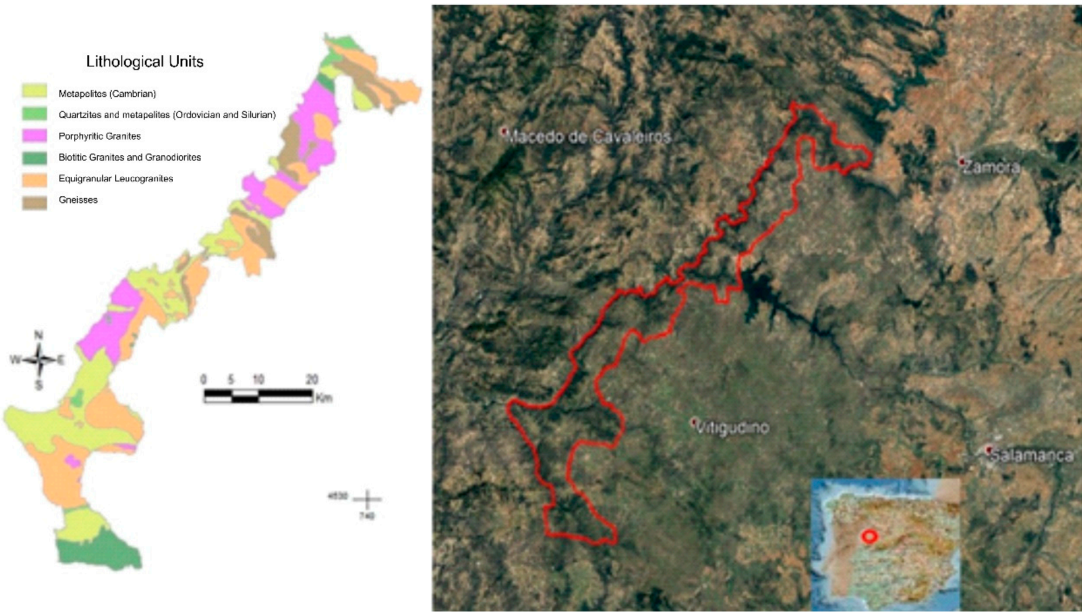

Figure 1. Geospatial distribution of the lithological units in the study area.

The Variscan Orogeny (Carboniferous age) affected these materials in various deformation phases, with there being structures in the NW-SE directions. The metamorphism that is associated with this orogeny transforms the sedimentary sequence into metapelites and gneisses, and it reaches a partial fusion with the generation and intrusion of anatectic granites [15–18].

Granitic rocks and the associated intermediate rocks, which intrude during the second phase of deformation D2 and up to D3 (older granites), show a great variety of rock types, some of which are represented in the Arribes del Duero Natural Park: leucogranites, biotitic granites and intermediate and basic rocks. The leukogranites contain two micas and of anatectic origin. They can be equigranular, i.e., fine-to-coarse grained, the latter sometimes occurs with tourmaline, garnet or cordierite and porphyritic. The biotitic granites are always porphyritic and can sometimes also have muscovite and/or cordierite. The intermediate rocks are spatially in relation to the biotitic granites and they vary in their composition from diorites and monzonites to tonalites and granodiorites [19,20].

All of this (granitic and metamorphic) basement is affected by the late Variscan and Alpine faults that condition the subsequent fitting of the river network. This fracturing has directions that run from NW-SE to E-W, although the most characteristic system has a NE-SW or NNE-SSW direction. Some of these faults are associated with large quartz dikes that constitute morpho-structural alignments of relevant ridges in the peneplain (the so called "Sierros") [21]. From the geomorphological point of view, the fluvial embedding on the peneplain is very representative since it occurs throughout the Quaternary, leaving some remnants of an ancient hanging surface (La Peña geosite) as a result of the intense process of alteration of the primary surface. These relict witnesses are of epi-syenite that are more resistant to the alteration processes.

3. Materials and Methods

Twelve sites were selected for the purpose of assessing their scientific, educational and tourist cultural interest in local and regional studies. Some sites are referred to in the National Inventory as places of Geological Interest (LIGs). The entire natural park is considered a Global Geosite (https://www.igme.es/patrimonio/descargas/BASES%20CONCEPTUALES%20Y%20METODOLOGIA%20DEL%20INVENTARIO%20ESPA%C3%91OL%20DE%20LUGARES%20DE%20INTERES%20GEOLOGICO%20(IELIG).pdf accessed on 30 July 2022). We have used the free Google Earth browser to make a virtual visit to these 12 geosites (Figure 2). The itinerary, from north to south, begins in Las Barrancas de Fariza (P-1) (Zamora Province) and ends in La Fregenada (P-12) (Salamanca Province).

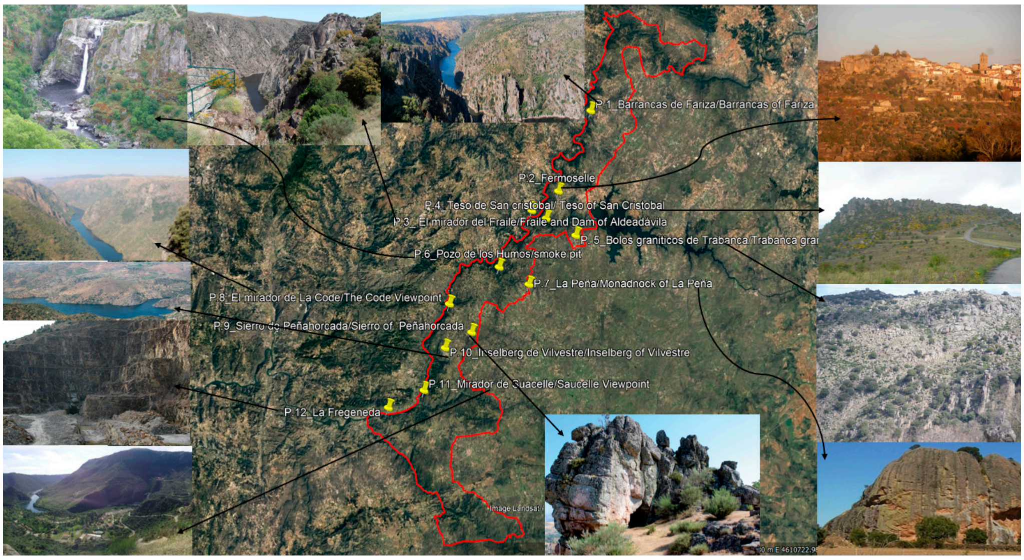

Figure 2. Arribes del Duero Natural Park with selected geological sites.

The augmented reality is applied here by implementing the different cartographic layers and digital information that are sometimes found on paper or by downloading and implementing layers from geoportals of public administrations (points of cultural interest). This includes digital georeferenced information on highways, paths, archaeological remains, delimitation of geoparks, biological heritage: protected fauna and botany, anthropic and natural singularities, areas of spectacular landscape, etc.). The participant can relate to their geological route in Google Earth. All of this transversal information can be found in the same (free) application (app) and in the same geospatial format, thus helping the teaching–learning processes by integrating inter-operable thematic layers in real time for the area that is being studied. It constitutes a teaching complement for field practices where the contents are observed directly by the naturalist scientist or tourist in the natural outdoor laboratory.

3.1. Assessment of Places of Geological Interest (LIGs) or Geosites

The method that was used to assess geosites is that which is proposed by García Cortés et al. [22]. This method consists of evaluating 18 parameters in each site based on their intrinsic value, weighted from 0 to 4 points (0 is the minimum interest, and 4 is the maximum interest), which are multiplied by different coefficients to obtain their scientific, educational and tourist cultural value (Tables 1 and 2). Where geosites are of international significance, different geosite valuation methods were used [23–26] with the Garcia Cortés et al. [22] being the most accepted and applied method for assessing sites of geoheritage significance in Spain [25,26].

Table 1. Parameters that were studied and coefficients based on the value that was sought (scientific, educational and tourist).

Parameters	Scientific	Educational	Tourist/Cultural
Representativeness	30	5	0
Character type locality	10	5	0
Degree of scientific knowledge of the location	15	0	0
State of conservation	10	5	0
Viewing conditions	10	5	5
Rarity	15	5	0
Geological diversity	10	10	0
Learning objectives/educational use	0	20	0
Logistics infrastructure	0	15	5
Population density	0	5	5
Accessibility	0	15	10
Intrinsic fragility (geosite size)	0	0	15
Association with natural and/or cultural elements	0	5	5
Beauty	0	5	20
Informative content/use	0	0	15
Potential for tourism/recreation activities	0	0	5
Proximity to recreational areas	0	0	5
Socioeconomic environment	0	0	10

Table 2. Data that were obtained from the evaluations of each parameter by stops and results of the scientific, educational and cultural interest of each geosite.

Parameters	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Representativeness	2	1	2	2	2	2	2	2	2	1	2	4
Character type locality	0	1	1	1	1	1	1	1	1	1	2	2
Degree of scientific knowledge of the location	2	4	4	4	1	4	4	1	1	1	2	4
State of conservation	4	4	4	4	4	4	4	4	2	2	4	2
Viewing conditions	4	4	4	4	4	4	4	4	4	4	4	4
Rarity	1	1	1	1	1	1	1	0	1	1	1	2
Geological diversity	2	1	4	2	2	2	2	2	1	2	2	2
Learning objectives/educational use	2	4	4	2	2	2	2	1	2	2	2	4
Logistics infrastructure	2	4	2	1	2	4	2	1	1	1	4	2
Population density	1	1	1	1	1	1	1	1	1	1	1	1
Accessibility	2	4	2	1	4	1	1	2	2	4	4	1
Intrinsic fragility (geosite size)	4	4	4	2	2	4	1	4	2	2	4	2
Association with natural and/or cultural elements	1	4	4	1	2	2	2	2	2	2	4	2
Beauty	2	2	4	2	1	2	2	2	1	2	2	4
Informative content/use	2	4	4	1	2	2	2	2	2	4	2	2
Potential for tourism/recreation activities	2	4	2	1	2	2	2	1	1	4	1	4
Proximity to recreational areas	0	0	1	0	0	0	0	0	0	4	1	1
Socioeconomic environment	4	2	1	1	4	1	1	4	4	4	1	2
TOTAL	**37**	**49**	**49**	**31**	**37**	**39**	**34**	**34**	**30**	**42**	**43**	**45**
ASSESSMENT OF SCIENTIFIC, EDUCATIONAL AND TOURIST CULTURAL INTEREST												
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**
Scientific interest	205	205	265	245	200	250	245	185	170	150	225	310
Educational interest	195	300	285	170	230	215	190	165	165	205	280	250
Tourist Cultural interest	240	305	300	145	215	220	160	235	185	290	255	240
Total	640	810	850	560	645	685	595	585	520	645	760	800

3.2. 3D Virtual Route on the Google Earth Platform

Once geosites had been identified, catalogued and assessed for their geoheritage significance, they were georeferenced with their GPS coordinates and geological context. For this, the Google Earth platform was used, which allowed us to place the points on a virtual 3D globe, as can be seen in the flowchart shown in Figure 3, in an area that was adjacent to Arribes del Duero Natural Park, thus obtaining georeferenced information in a simple and free-of-charge way that is suitable for all of the types of electronic devices, such as mobile phones, tablets, computers, etc. This makes it possible for the information that was collated to be accessible from anywhere, either in the classroom or on route between stops, thus facilitating the visualization of the itineraries by users and increasing their interest in the activity. The reference system that was established is the usual one that is used in Spanish cartography: Universal Transverse de Mercator—UTM [27]. Each geosite was georeferenced by means of a series of position marks, in which the spatial coordinates and a brief description of the area were shown (Figure 4). It also includes an information sheet with field photographs, interpretation of the information and evaluations of its scientific, educational and tourist cultural value (Figure 5).

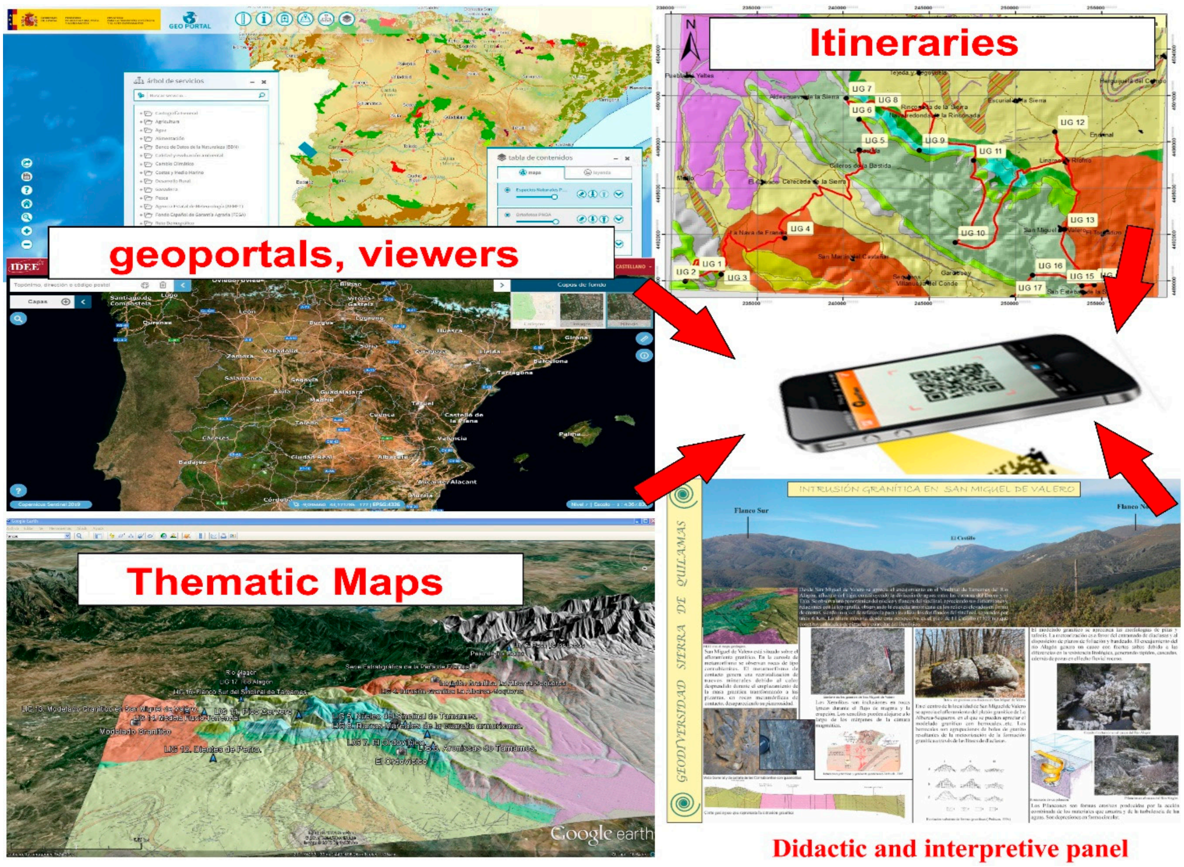

Figure 3. Graphical flowchart to understand the procedure and loading of layers in final implementation on smartphone.

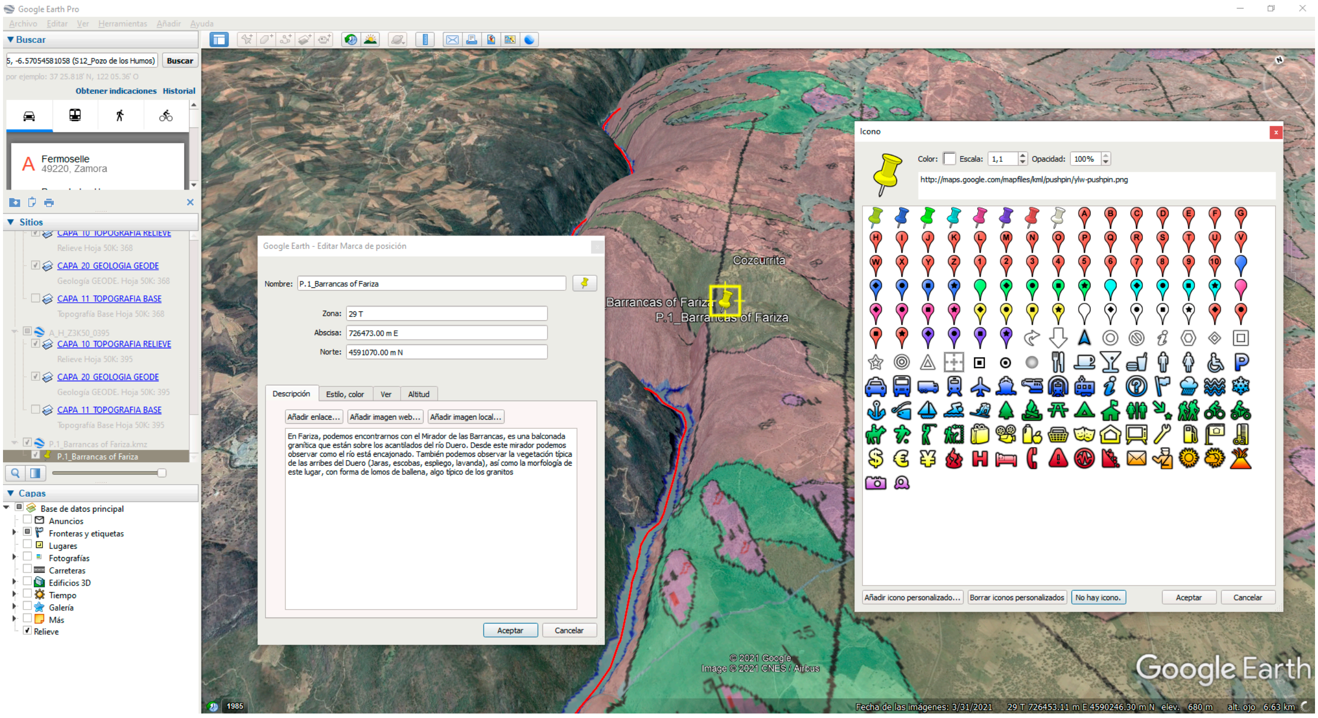

Figure 4. Screenshot of site P-1 (Barrancas de Fariza) with UTM coordinates, description and geological cartography.

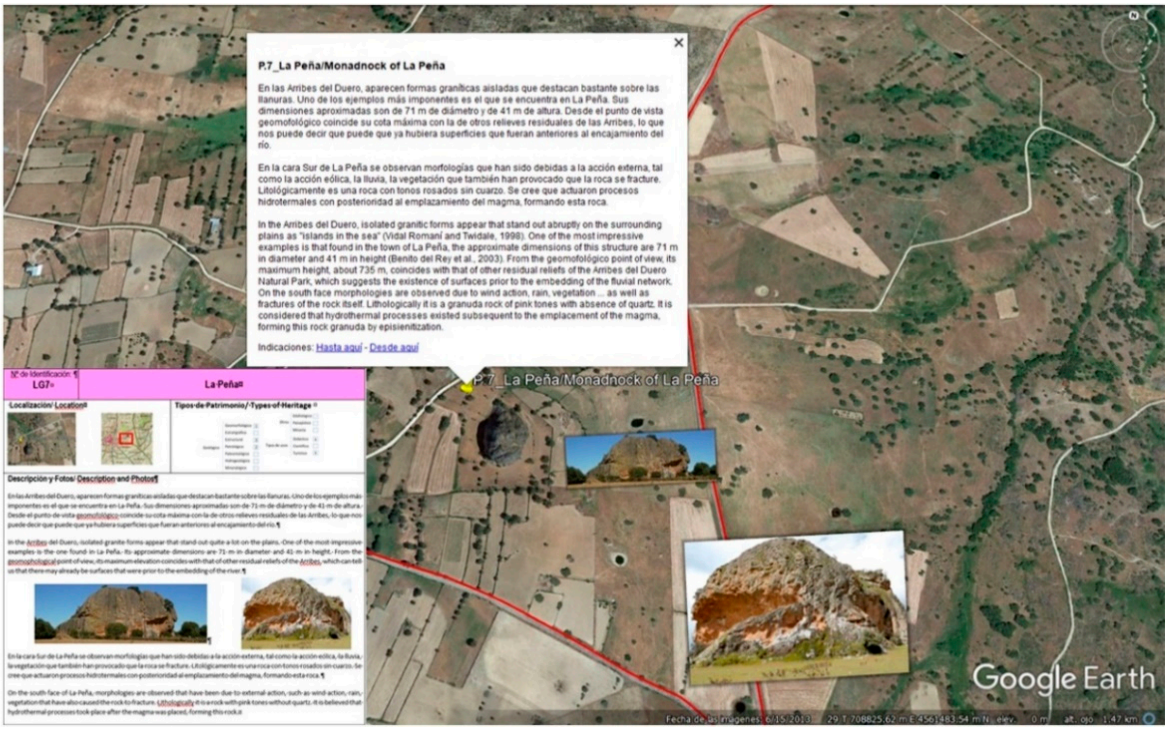

Figure 5. Screenshot of geosite P-7 (La Peña) with photos and sheet of geosite.

The set of sites, or stops, of the itinerary in “kml/kmz” format generated a geodatabase, and the platform automatically georeferenced each selected site. With the virtual 3D digital model [28,29], by activating the option “Relief”, one can zoom in on the sites in the itinerary, and by activating “analyze the geological and geomorphological context”, one can obtain a spatial visual of the area. In addition to adding alphanumeric and text information, photographs were added to each site, as well as a file with their description and interpretation (Figure 5).

When all of this information was available for each site, the Google Earth platform generated a virtual route. The application generated the route by road or through other areas depending on the mode of movement from one site to another (by car, hiking, etc.). To do this, the departure and arrival sites must be selected, and the application will generate a route to follow like any other global positioning system would (Figure 6).

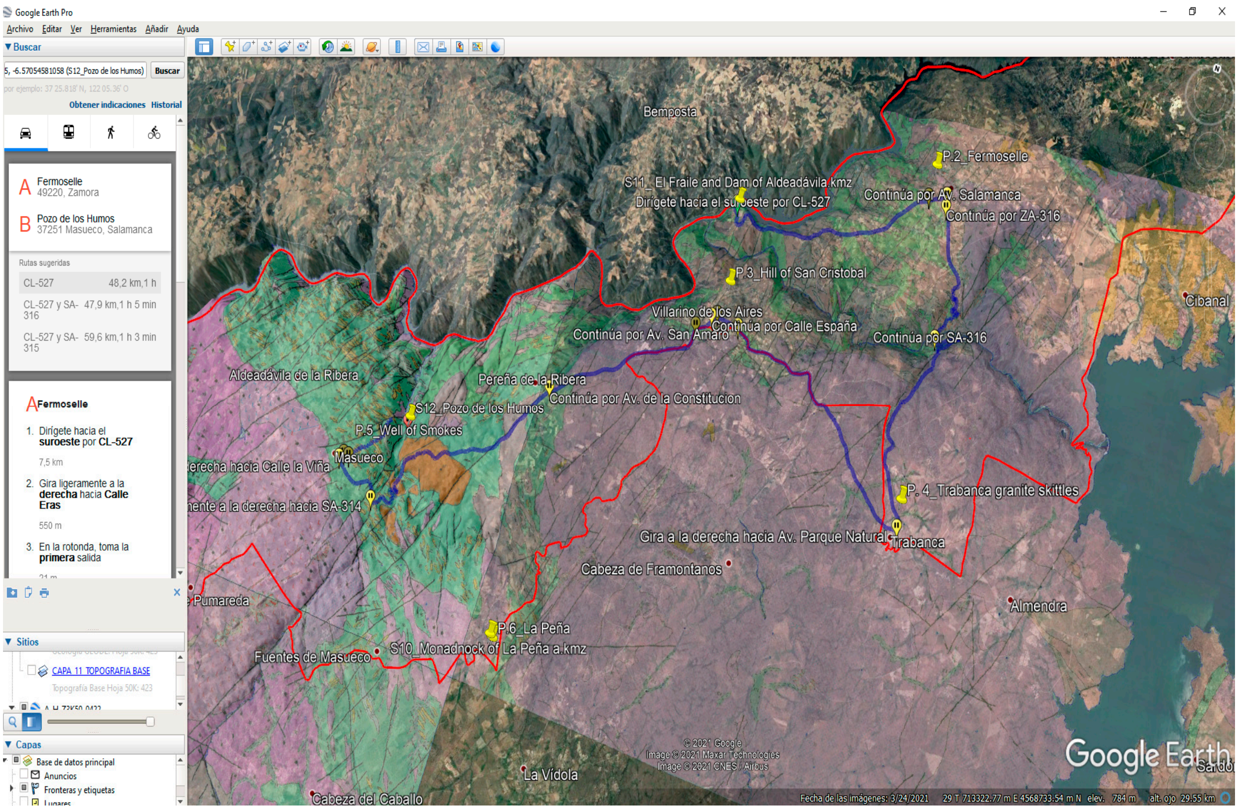

Figure 6. Capture of one of the possible routes that was generated by Google Earth (blue line) on the geological cartography with transparency on the orthophotography. Route from Mirador del Fraile to the Pozo de los Humos. Red line: limits of the Arribes del Duero Natural Park.

By interacting with the Street View application of Google Maps, structures or outcrops can be viewed “in situ” (Figure 7). In addition, a topographic profile of the route can be generated, allowing one to previously assess its complexity (Figure 8).

Figure 7. Capture on the selected route in "Street View" mode. Entrance to the Arribes del Duero Natural Park. Box on the left with GPS tracking. Bottom right: view of the La Peña geosite (P-7) from the route.

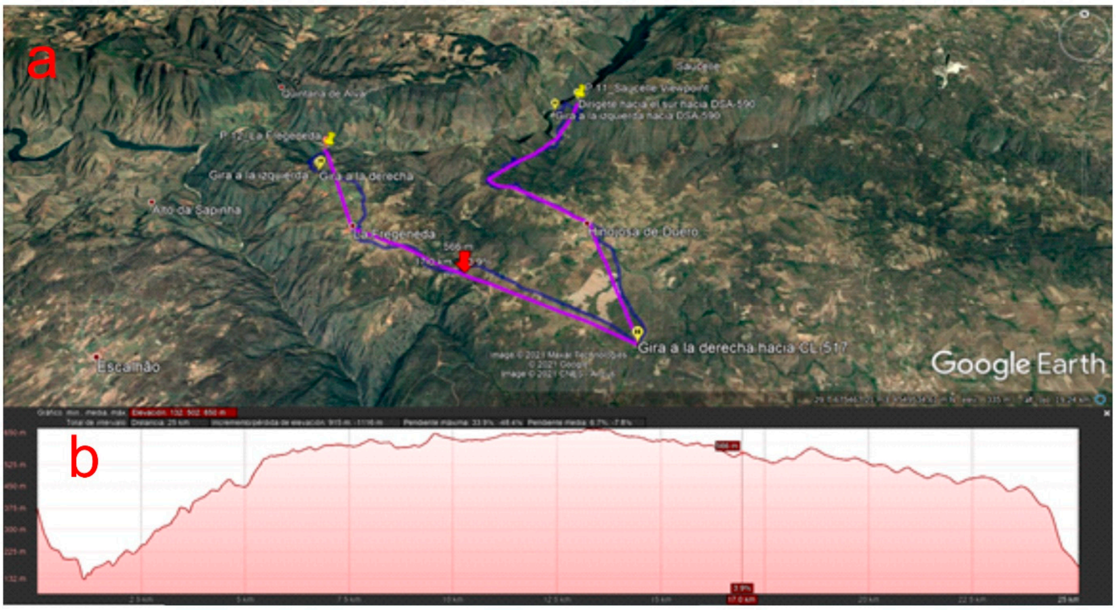

Figure 8. Route from site P-11 (Mirador de Saucelle) (**a**) to site P-12 (La Fregeneda) and topographic profile (**b**).

Users can perform a 3D virtual flight using the command "record route". The flight includes a tour on the geological map that is superimposed on the 3D virtual globe for the route that is selected for the different geosites, with them being able to access the photographs of each stop and the information on the corresponding sheet [30]. The resulting virtual flight will be a recreation of the virtual 3D video which will be compatible with tablets, computers or mobile devices. The virtual tour of the selected itinerary can be presented in different video formats: mp4, avi, etc. (Video S1).

Another application that was implemented in the virtual route which provides height interactivity between students is the flight simulation mode, which allows one to choose a type of aircraft, activate the flight in a specific position, or establish the departure airport from anywhere on the globe (Figure 9).

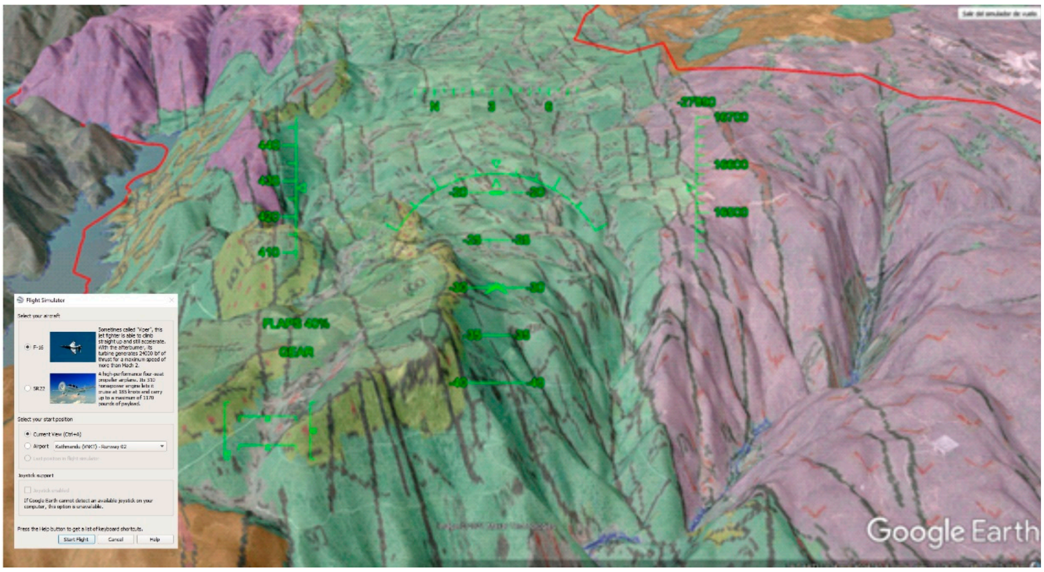

Figure 9. Capture of the virtual flight with the flight simulator of the F-16 plane over the geological distribution near of the site P-11 (Saucelle).

3.3. Educational Resources: Field Guide and Geoapp

Field Guide. A field guide was developed that includes sheets with basic information on each site, which were made with all of the materials, both descriptive ones (coordinates and field data) and graphic ones (photographs and diagrams). The guide includes questions about geological materials, structures, etc., which appear in each of the sites on the route that the participants will have to solve. This allows the participant to understand the main geological concepts. The field guide is available in PDF format, accessible with a QR code, or downloadable through a teaching platform.

Applications. Another educational resource that is presented is the creation of an app, which is free for the android operating system. Only internet access is required for its use. The application allows the information of the proposed route to be displayed by entering the data of each geosite into the platform assistant. In addition, one can obtain additional information on Google Maps, send messages directly to the mobile phones of all of the users regarding real-time information about the geosites, as well as attach links. The information that is included is in Spanish and English.

4. Results

4.1. Itinerary and Geological Heritage

The 12 stops (Figure 10) on the itinerary are located in Barrancas de Fariza (P1) and Fermoselle (P2) in the province of Zamora, while the other stops: Mirador del Fraile (P3), Teso de VillarinoSan Cristobal (P4), Berrocales de Trabanca (P5), Pozo de los Smokes (P6), La Peña (P7), Mirador de La Code (P8), Sierro de Peñahorcada (P9), Inselberg de Vilvestre (P10), Mirador de Saucelle (P11) and La Fregeneda (P12) are located in the province of Salamanca. Most of the stops are accessible by car or bus. Table 2 shows the evaluations of the 12 stops with their total value and the value of the scientific, educational and tourist cultural interests.

Figure 10. (**A**) Incision of the Duero River in the granite basement and formation of watercress-limes. (**B**) Granite sill highlights on migmatites. (**C**) Image of the flaking of the granite of the Mirador de El Fraile on the left and on the right the dam of the Aldeádavila Dam on the Duero River. (**D**) View of Cerro de San Cristóbal on the left and a rounded granite fragment, which is fractured in two parts on the right. (**E**) Landscapes and granite forms scattered around the Trabanca berrocal. (**F**) Pozo de los Humos waterfall.

4.2. Description of the Stops

Stop 1 (P1): Barrancas de Fariza (4,591,070.00 m N/726,473.00 m E).

The Mirador de las Barrancas, in the municipality of Fariza, consists of a granite balcony that is located on the cliffs of the Duero River. From this viewpoint one can see the confluence of the river. One can also observe the typical vegetation of the Arribes del Duero (rockrose, brooms and lavender), as well as its geomorphology (shaped like the back of a whale), which is atypical for granites (Figure 10A).

This first stop has a scientific interest value of 205, a didactic interest value of 195 and a tourist or recreational interest value of 240. In total, this stop has 640 points which reflect the sum its scientific, educational and cultural interest.

Stop 2 (P2): Fermoselle (4,577,492.00 m N/717,530.00 m E).

The town of Fermoselle, located to the SW of the Province of Zamora, constitutes an example of popular architecture that is adapted to the granite environment. One can also see the great embedding of the Duero River.

Fermoselle's geology includes metamorphic rocks (migmatized gneisses and metapelites) and granite rocks. The granites, which are more resistant to erosion when they do not present a high degree of fracturing, the hills and the metamorphic rocks are located at lower elevations, forming smooth slopes like those of the Duero Valley (Figure 10B). Many houses have been built on granite, and there is an extensive network of cellars which have been dug out of the softer migmatitic rocks [31,32].

This stop has a scientific interest value of 205, a didactic interest value of 300 and a tourist or recreational interest value of 305. In total, this stop has 810 points.

Stop 3 (P3): Mirador del Fraile (4,574,916.00 m N/711,807.00 m E).

At the Fraile viewpoint, one can see the Duero River canyon and the granite modeling (bell-shaped domes and berrocales). Desquamation processes are abound, causing slabs and rounded shapes that are in favor of the river valley (Figure 10C). The Aldeadávila Dam is 139 m high, and there is 848,000 m^3 of water in its reservoir. Its construction is represented a milestone in hydraulic engineering due to the large slopes and very complicated access points. In addition, the fractured granite massif has high permeabilities.

This stop has a scientific interest value of 265, a didactic interest value of 285 and a tourist or recreational interest value of 300. In total, this stop has 850 points.

Stop 4 (P4): Cerro De San Cristóbal (4,572,935.00 m N/714,265.00 m E).

It is located in the municipality of Villarino de los Aires. From this place, one can see the setting of the river Tormes near its mouth in the Duero, which has the structural characteristics of the old geological base. The views of the arribes del Tormes and granite outcrops with rounded morphologies forming berrocales stand out, and numerous fractures can be seen. From the site, one of the granite sills is cut by the river Tormes (Figure 10D). These granite bodies sometimes give rise to large waterfalls.

This stop has a scientific interest value of 245, a didactic interest value of 170 and a tourist or recreational interest value of 145. In total, this stop has 560 points.

Stop 5 (P5): Berrocal de Trabanca (4,568,747.00 m N/719,212.00 m E).

Located near the town of Trabanca, one can see striking berrocales, in this case, on two-mica, equigranular, medium-grained granites (Figure 10E).

This stop has a scientific interest value of 200, a didactic interest value of 230 and a tourist or recreational interest value of 215. In total, this stop has 645 points.

Stop 6 (P6): Pozo de los Humos (4,565,742.00 m N/703,656.00 m E). The Pozo de los Humos is located between the municipalities of Masueco and Pereña. It corresponds to a spectacular waterfall of the river Uces which is 50 m high, with a great flow in spring that originates in its fall large aerosols (the so-called "smokes"). The visualization of this geosite makes it possible to easily observe the structural relationships between the different lithologies, observing sub-horizontal granite sheets that are alternating with the metapelitic nesting rocks of slate [31] (Figure 10F).

This stop has a scientific interest value of 250, a didactic interest value of 215 and a tourist or recreational interest value of 220. In total, this stop has 685 points.

Stop 7 (P7): Inselberg de La Peña (4,561,397.00 m N/708,641.00 m E).

In Arribes del Duero, isolated granite forms appear that stand out on the peneplain (inselberg). One of the most impressive examples is the one in the town of La Peña. Its approximate dimensions are 71 m in diameter and 41 m in height. From the geomorphological point of view, its maximum elevation coincides with that of an old surface that has remained as a residual relief on the peneplain, which allows one to know the existence of value surfaces that were visible prior to the encasing of the Duero River. On the south face of La Peña, morphologies are observed that due to the wind action, generate gnammas and taphonis that are cavities which were formed by the attrition of the particles that the wind dragged against the rocks (Figure 11A).

Figure 11. (**A**) Image of the rock seen from the front (top), which stands out on the current surface (bottom left) and with important structures of wind erosion (bottom, right). (**B**) View of the riverbed of the Duero river from the La Code viewpoint. (**C**) Panoramic view of the Sierro de Cerezal de Peñahorcada and detail of the quartz dike at its highest point where it is resistant to erosion (top right and left). (**D**) Capture of a panorama from the Bajo Duero de Vilvestre (above). In the lower part, one can see the town of Vilvestre with the elevated sector of El Castillo (left) and the pyramidal morphologies near the viewpoint in the riverbed (right). (**E**) Panoramic of the folded Ordovician materials on the Portuguese slope (top) and view of the softer slope (bottom left) and lower part of the slope with crops and terraces (bottom right). (**F**) Location of the La Fregeneda stop on the geological cartography wherein there are visible abundant pegmatite dikes (yellow), detail of the dikes in a section of the road (top left), and a view of the cut from Mina Feli (top right) where hydrothermal seams with cassiterite are cut by discordant pegmatites. Feli Mine view (top right) and hydrothermal quartz seams in reel cuttings (top left). One can also appreciate the previous stop of the Mirador de Saucelle and the Ordovician reliefs in the Portuguese part or right bank of the Douro River.

Lithologically, the rock is an epi-syenite, and with striking pink-two-reddish tones that were caused by the hydrothermal alteration of the granite.

This site stands out for its petrological, geomorphological and tectonic features.

This stop has a scientific interest value of 245, a didactic interest value of 190 and a tourist or recreational interest value of 160. In total, this stop has 595 points.

Stop 8 (P8): Mirador de La Code (4,560,698.00 m N/692,950.00 m E).

From this viewpoint, one can see the incision of the Duero (Figure 11B). The great difference between the peneplain and the steep slope can be appreciated. In the valley area, there is a mild and attenuated climate while, on the peneplain, the temperature and rainfall profile is more continental [33,34]. In these fluvial incisions, the vegetation is conditioned by the changes in the temperature and altitude, as well as by the rainfall. The geographical limitations that occur due to the slope have slowed down the expansion of the agricultural and livestock activities, which is why this has helped to conserve the vegetation species that have a great ecological importance (such as rockrose, brooms and lavender).

The geosite has a scientific interest value of 185, a didactic interest value of 165 and a tourist or recreational interest value of 235. In total, this stop has 585 points.

In the west of the province of Salamanca, the elongated elevations that stand out from the monotony of the peneplain are called "sierro". Their heights can reach 60 to 80 m, and their lengths can be a few kilometers (Figure 11C).

These structures only develop within the granite and are characterized by the presence of dikes and quartz veins at their highest levels and slopes of altered granite (which are crumbly, without berrocal and without vegetation, which is used for cultivation in the plots that are perpendicular to the top). In contrast, the surrounding peneplain shows granite berrocal and is covered by shrubs and trees.

The formation of these mountains is linked to a family of (probably) tardivariscas fractures, although they may possibly rejuvenated later, with a very constant NNE direction (N20E to N35E). The repeated operation of these structures causes the fracturing and alteration of the granite in their vicinity, with the migration of the quartz to the central areas, which later remain as higher projections due to their greater resistance to erosion.

This stop has a scientific interest value of 170, a didactic interest value of 165 and a tourist or recreational interest value of 185. In total, this stop has 520 points.

Stop 9 (P9): Sierro de Cerezal de Peñahorcada (4,554,710.00 m N/696,144.00 m E).

Stop 10 (P10): Inserberg de Vilvestre (4,552,812.00 m N/690,603.00 m E).

This inselberg has a residual relief which is a highlight. These reliefs appear to coincide with harder levels of lithology, in which the structural platforms have the shape of tables (Figure 11D). It constitutes a conical inselberg that developed where the structural elements present a great resistance to erosion. In the area, which is known as the Bajo Duero, one can find morphologies that are not so abrupt. They have acid soils with a sandy texture that are poor in carbonates and with very little organic matter content, which is characteristic of granite substrates so they are not very fertile for agriculture and livestock.

This stop has a scientific interest value of 150, a didactic interest value of 205 and a tourist or recreational interest value of 290. In total, this stop has 645 points.

Stop 11 (P11): Mirador De Saucelle (4,545,817.00 m N/685,100.00 m E).

The viewpoint is located between the town of Saucelle and the dam of the same name. It can be seen that this stretch of the river has meanders since it is not as entrenched as it is upstream. From this viewpoint, one can see the Portuguese massif of Penedo Durao, highlighting the structural and tectonic aspects of the area (Figure 11E)

The most abundant rocks in this area are hillside colluvium and alluvial deposits that were left by the river. The softer slopes are present, which allows one to work the land more easily, and one can appreciate that there are large areas with vineyards on the metamorphic rocks (slates, gneisses and schists) and fewer vineyards on the acid soils that have developed on the igneous rocks (granites). The presence of the terraces indicates differential erosive activity in the steepest parts of the slopes.

This stop has a scientific interest value of 225, a didactic interest value of 280 and a tourist or recreational interest value of 255. In total, this stop has 760 points.

Stop 12 (P12): La Fregeneda (4,543,948.00 m N/ 677.779.00 m E).

La Fregeneda is located northwest of Salamanca on the border with Portugal. The sector is characterized by a swarm of discordant and concordant pegmatitic dikes that are rich in lithium which is associated with the hydrothermal quartz veins with tin mineralization (cassiterite). These pegmatites are embedded in a complex schist and have a great morphological variety. The Feli mine stands out (Figure 11F) where these hydrothermal quartz which form a seam with the cassiterite are observed to be cut by the lithium-rich pegmatite dikes.

This stop has a scientific interest value of 310, a didactic interest value of 250 and a tourist or recreational interest value of 240. In total, this stop has 800 points. This stop is the third one with the highest score and it also has a very high educational score.

Generally, the value of the degree of interest (scientific, didactic and tourist-recreational) which was observed for all of the stops is high. There are some stops that have a higher tourist or scientific interest value than the educational one, but in this case the interested is in those of greater educational value to establish the itinerary with the students.

The highest scientific values are at stop 12 (La Fregeneda) with 310 points, stop 3 (El mirador del Fraile) with 265 points, stop 6 (El Pozo de los Humos) with 250 points, stops 4 (Cerro de San Cristobal) and 7 (La Peña) with 245 points, stop 11 (Mirador de Saucelle) with 225 and stops 1 (Barrancas de Fariza) and 2 (Fermoselle) with 205.

Regarding the educational value, stop 2 (Fermoselle) stands out with 300 points, stop 3 (El mirador del Fraile) has 285 points, stop 11 (Mirador de Saucelle) has 280 points, stop 12 (La Fregeneda) has 250 points, stop 5 (Bolos graniticos de Trabanca) has 230 points, stop 6 (Pozo de los Humos) has 215 points and stop 10 (Inselberg de Vilvestre) has 205 points.

The highest tourist/recreational value corresponds to stop 2 (Fermoselle) which has 305 points, which is followed by stop 3 (El mirador del Fraile) with 300 points, stop 10 (In-selberg de Vilvestre) with 290 points, stop 11 (Mirador de Saucelle) with 255 points, stops 1 (Barrancas de Fariza) and 12 (La Fregeneda) with 240 points, stop 8 (La Code) with 235 points, stop 6 ("Pozo de los Humos" Well of Smokes) with 220 points and stop 5 (Granitic bowling of Trabanca) with 215 points.

4.3. Didactic Resources

With all of the information about the geosites (photographs, diagrams, spatially georeferenced coordinates, etc.), the field guide and app were designed so that the route would be more interactive and the students could perform dynamic participation during their completion of the itinerary. These resources are freely available and downloadable from the "cloud" through the Internet for students, teachers or any other participant on the route.

The field guide (Figure 12) contains the detailed information of the stops and graphic documentation such as photographs and interpretive diagrams, as well as different activities that are related to the geological concepts and general questions of the content of the curriculum. These activities deal with aspects of basic concepts, the recognition of structures and rocks, as well as geodynamic geological processes that occurred over time and the geological history of each stop. The activities can be carried out individually or in groups, and they take place during the completion of the itinerary, although some can be performed later at home. These exercises and questions will help the student to specify what has been learned and to consolidate the main ideas and concepts (Figure 12).

The field guide is available for printing and it was also uploaded to the educational center platform. Using a QR code, it will be easier to download it, and it can be viewed from any electronic device. A reference is also made in the app to a section of the field guide to facilitate its download.

Figure 12. Cover page of field guide and QR code. Screenshots of the geoapp: in the first screenshot there is the welcome message, both of them are in English and in Spanish, the different sections that the app has, the content of stop 12 (La Fregeneda), both of them in English and Spanish, and the group chat and the section on incidents and suggestions.

A positive feature of this application is its accessibility as it is free and downloadable for Android systems. All one needs is internet access. On the first screen, when the app is opened, a welcome message appears explaining the content of the app and how it works. Next, the main menu appears where all of the stops have been presented with the data and photos of the route. At the beginning of it, one can find a link to Google Earth, and in the next section, an image or diagram of the complete route. Subsequently, all of the LIGs appear with their information and photographs. It features a chat room for the users to interact with each other and forums for the participants to raise issues and/or questions. The content of the Geoapp is in Spanish and English in order to expand the range of users in schools and institutes that are bilingual. There is also access through a Google drive link to the field guide, where one can find more information on each stop and exercises to evaluate the skills that are learned using the itinerary. The application will be able to be downloaded through a link or using a QR code so that it is easily accessible (Figure 12).

The augmented reality application that is proposed in this work integrates specific thematic cartographies (geological, vegetation, topographic, etc.) with cartographies that identify points of natural interest: geological, biological, historical, cultural, etc., in the same free application (Google Earth) and that allows one to implement, using the same inter-operable format, the different usable and downloadable layers of the geoportals of the official web pages, but that are scalable, that is, for a specific territorial sector. One can establish the options of greater spatial and temporal resolution, or even incorporate, for example higher quality digital terrain models or satellite images or drones (centimetric pixel size resolutions), thus improving the route information in real time and ensuring that they are geopositioned using the smartphone's GPS, which can facilitate the photo-interpretation of, for example, natural processes: landslides, geological risks, outcrops and geospatial distribution, etc. Technological progress occurs very quickly, and the information and its associated databases currently require applications that can interact with high-resolution information that is as up-to-date as it possibly can be, and the methodological proposal of this work allows it to be applied at the teaching level and integrated into activities of teaching and learning.

The georeferenced geographic information, as indicated in the previous point, was obtained from the websites, viewers and geoportals of the different public administrations of the state. Currently, although this information is implemented using different GIS types, the formats are inter-operable and easy to transform, so even if the native digital information is downloaded in a "shapefile" format from any GIS type, or from other programs for daily use such as autocad (formats dwg, dxf, dgn, etc.), they can be automatically converted to kml/kmz formats, which allows the different thematic tents to be transformed into a reference system that can be used worldwide, such as the wgs84 reference system, which is the one that is usually used by the GPS. This makes things easier since each country establishes different official reference systems for its official cartography, but the method that is indicated in this article generalizes and transforms them directly into an interoperable format. It constitutes in itself a strategy for the future since, in the end, the inter-operable free application is the one that will survive possible specific applications and those of specific groups.

5. Conclusions

A virtual geological route has been designed through the Arribes del Duero Natural Park that can provide educational resources to integrate the areas of geological interest at different educational levels and for all people.

The teaching resources that were used such as the field guide and the geoapp help to make the tour more entertaining and educational for the students. In addition, the geomatics that was applied with the tools that are available on the Google Earth platform allows us to implement augmented reality using a smartphone for its daily use in student life and interact with the generated resources such as the flight simulator, 3D maps, Street view, etc. They will make this experience fun as well as educational.

The designed geological route includes 12 geosites (Places of Geological Interest, LIG), which have been weighted according to their didactic, scientific and tourist cultural interest. All of the stops have a high interest value, although some have a higher tourist or scientific interest value than the didactic one (Supplementary Materials).

Of the 12 evaluated stops, those with the highest didactic scores are stops 2 (Fermoselle), 3 (Mirador del Fraile), 11 (Mirador de Saucelle) and 12 (La Fregeneda), and this allow one to design possible personal itineraries. There is no time to complete all of them in one day and group them by content or proximity. Stop 2 is in the Province of Zamora and stops 3, 11 and 12 are in Salamanca. They are easily accessible areas by road when one is using a minibus. The fact that students can see things with their own eyes makes them more curious and interested in geology. This also encourages both sustainable geotourism in economically depressed areas, such as the one that has been studied, as well as promoting careful attitudes towards the environment. The geosites of Arribes de Duero that are most unique due to their high educational value may in the future be subject to a more detailed analysis (case-study) of the use and evaluation of the application of different pedagogical methodologies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11111916/s1, Video S1: Kml Geodatabase, video virtual tour.

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Landscape Analysis of the Arribes del Duero Natural Park (Spain): Cartography of Quality and Fragility

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Abstract: The landscape is a resource to be considered in the planning and sustainable management of the territory of natural spaces, such as the Arribes del Duero Natural Park. It is conditioned by environmental factors. They are highly influential on the quality of life of the people who live there. A historical analysis of the landscape was carried out with a qualitative and partially subjective character. In this work, we took advantage of current technologies, such as GIS techniques, to objectively and quantitatively calculate the variables. Firstly, it was necessary to draw up a map of landscape units, which is derived from the union of the abiotic (geomorphology and lithology) and biotic (vegetation) components in the background. Twelve homogeneous landscape units were identified by analyzing the quality and perceptual fragility of each one and considering intrinsic and extrinsic factors. The results obtained showed that the landscape quality presents areas with very high values in the fluvial canyon of the Duero river. The lowest values were found in very degraded and vegetated polygenic areas. On the other hand, the most fragile areas were those with some vulnerable character that prevents the development of human activities, such as areas with steep slopes. The procedure and results obtained constitute a useful tool for public administrations to carry out sustainable management of natural areas.

Keywords: landscape units; landscape quality; landscape fragility; GIS; Arribes de Duero

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1. Introduction

The term "landscape" integrates a set of natural elements: rocks, water, air, plants, and animals that interact with human beings, their arrangement, and their distribution in a territory [1–3]. Thus, the study of landscape has been developed on the basis of different disciplines, such as geology, geography, architecture, and biology, generating different definitions and constituting a multisensory perception of a system of ecological relations that differentiates a perceptible and an imperceptible part, and a functional and causal factor, respectively [4].

The landscape represents a resource that establishes the degree of naturalness and integrity of the natural environment; therefore, its preservation is key to the quality of life of the population. For this reason, our society has developed a set of procedures that guarantee its protection with correct spatial planning through strategic and impact assessments [5–11].

A correct analysis of the landscape implies the study of the components of the physical environment, since it is a result of the interaction of all of them. They are as follows: geology, geomorphology, climate, edaphology, vegetation, hydrology, fauna, and anthropic activities. Geomorphology is the primary component, because it defines the main landforms, considering the morphogenetic processes triggered by the agents that caused the erosion and deposition that gave rise to the Earth. The second most important is geology, because its resistance to external geodynamic agents affects the different geological materials, producing rocks of different coloring and causing effects on the spatial structure of the landscape [12,13].

Another component of the physical environment, which affects the perception of the landscape at a more detailed level, is the plant formations. These determine the spatial structure and affect its texture according to their heights (trees, shrubs, herbaceous species) and types (deciduous or evergreen), characterizing the visible background [13–15].

By comparison, low population density and uneven distribution generate a variety of interconnected landscapes, so that land exposed to little human intervention tends to be more natural [14,15].

In order to carry out this landscape analysis in a simpler way, different studies [Natural heritage mapping of the las Batuecas-Sierra de Francia and Quilamas Nature Parks (SW Salamanca, Spain); Characterisation of the Susceptibility to Slope Movements in the Arribes Del Duero Natural Park (Spain); When landscape planning becomes landscape governance, what happens to the science?; Progress in the remote sensing monitoring of the ecological environment in mining areas; Spatial distribution and influencing factors of settlements in the farming–pastoral ecotone of Inner Mongolia, China; Multitemporal analysis of land-use changes and their effect on the landscape of the Jerte valley (Spain) by remote sensing] have opted for the implementation of geographic information systems and remote sensors. These allow landscape studies of areas of special interest to be carried out with the support of spatial data analysis programs that are more precise in determining the temporal dynamics of the landscape, and have led to a significant leap in landscape concretization [16–21].

Currently, there are different methods for landscape analysis. On the one hand, there are indirect methods, which study the total landscape or phenosystem (sensitive part); on the other hand, there are direct methods, which study the visual aspect or cryptosystem (intangible part).

The use of indirect methods has increased since 2000 due to advances in GIS [22,23]. These methods identify the distribution of landscape components, in interrelation with thematic components of the natural environment (relief, vegetation, hydrogeology, etc.) [24,25]. They are the first factor used to describe the interrelationship between space and process in ecological systems and multi-scale analyses of landscape heterogeneity [26,27].

Direct methods, prior to indirect methods, assess the natural environment on the basis of aesthetic criteria or the perception of forms as visual, auditory, or olfactory sensations [22,28,29]. In natural spaces, the analysis of the landscape will allow the correct location and arrangement of elements and uses of the territory. It will show the degree of acceptance and the impact of the use of the physical environment by anthropic activities. The landscape constitutes a meeting point between technical, scientific, social, and political aspects and allows civil participation in land-use planning proposals [28,30].

The aim of this work was to identify the landscape units that make up the Arribes del Duero and to capture their quality and fragility in different cartographies, considering the components and elements that make it possible to establish the degree of singularity and representativeness for rational land-use planning.

2. Materials and Methods

2.1. Study Area

The area in which this study was carried out is the Arribes del Duero Natural Park. It is made up of 38 municipalities and has a population of 17,000 inhabitants (Figure 1). This area was declared as protected in 2002 [31], has a surface area of 1061 km^2, and is located to the west of the provinces of Salamanca and Zamora, bordering Portugal. The study area is characterized by two climates in the valley area: mild winters and very hot and long summers with an average temperature of 17.1 °C and rainfall of 500 mm. The climate in the plains is extreme continental, with temperatures of 12.2 °C and rainfall of 750 mm [32]. The landscape is characterized by an undulating peneplain (with a uniform height of 700–800 m) and by the steep slopes formed by the canyons (with heights of 130 m) carved by the fluvial system (Duero, Tormes, Uces, Huebra, and Águeda rivers). In terms of vegetation, the lowland areas are characterized by a rich mosaic of species, e.g., Quercus genus (holm oak, Spanish oak, cork oak, and gall oak), mixed with other tree species (ash) and scrubland (scrubland and broom), pastures, and dry crops (wheat, barley, rye, and vines). Meanwhile, on the slopes, olive and almond trees are cultivated using cultivation techniques such as terraces or "banccales", only to be displaced by oak and holm oak groves and juniper groves where agricultural use has been abandoned [33,34]. It should also be noted that there are large dams and hydroelectric power stations. It is one of the areas with the greatest hydroelectric potential on the Iberian Peninsula.

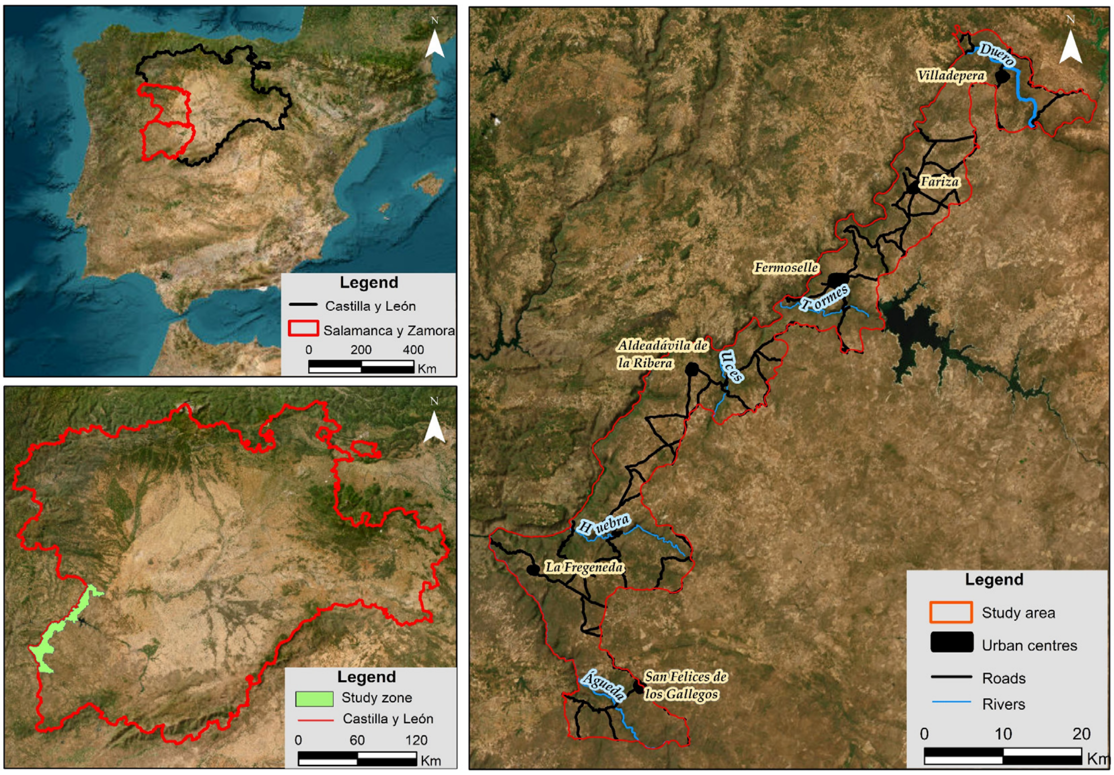

Figure 1. Study area.

2.2. Cartography of Natural Landscape Units

The methodological scheme used in this study to map the landscape units (Figure 2), was carried out in two phases. The first was the creation of parametric cartographies that define the components of the landscape (geological, geomorphological, vegetation, hydrology) [28,30,35]. To do this, intensive photo-interpretation work was carried out on the aerial photography of the 1957 American flight and also on orthophotos from more recent years, i.e., 2004, 2020, and 2023. This phase made it possible to define the characteristics of the different units on the basis of the natural components and to delimit their territorial extension. The most significant components are [12,28]:

- The geomorphological component: This is obtained on the basis of the cartography of geomorphological units, and it is synthesized into a cartography of geomorphological domains. Then, these domains are grouped according to their representativeness in the landscape.
- The lithological component: The lithological zoning was obtained from the geological cartography and used to generate the lithological cartography, which was then synthesized into lithological units with a landscape impact.

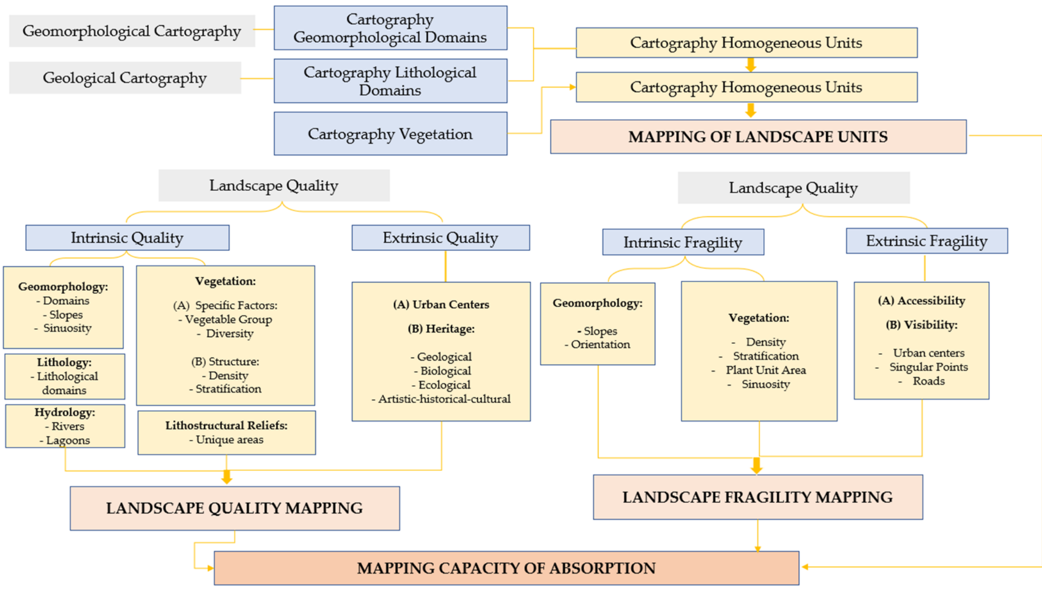

Figure 2. Methodological scheme.

In the second phase, several field campaigns were carried out to determine and characterize the landscape elements that define each of the units or sectors, which were grouped on the basis of the different components studied previously. The texture of the environment, scale, relief distribution, height, and horizontal stratification of tree species or color were observed [12,28,36].

The above components were grouped using map algebra and GIS techniques to obtain the cartography of homogeneous units. The cartographies of the components of the physical environment were simplified based on the elements and their visual analysis in the territory, by studying the degree of visibility and representativeness of each component. In addition, some of them needed to be eliminated and/or grouped according to the following criteria [12,28]:

- ✓ Smaller, scattered units that are perceptually unrepresentative should be included in larger and more conspicuous units.
- ✓ Those units that are similar to others should be integrated into the dominant group.
- ✓ Units that constitute relatively homogeneous portions of the terrain, in their environmental conditions and landscape components, should be grouped with those of greater perceptual impact.

Once the geomorphological and geological components were studied, the analysis of the third component involved in the landscape, the biotic factor, conformed by vegetation, was performed [12,28]. This component was obtained from the simplified cartography of vegetation units, resulting in a synthetic cartography for use in landscape.

Finally, considering the cartography of homogeneous units (geomorphology and geology) and vegetation cartography, a cartography of natural or environmental units of the landscape was generated [12,28].

2.3. *Landscape Quality Cartography*

The analysis of landscape qualities serves to identify areas where the aggregation of its components shows greater relevance, uniqueness, and importance, and require greater preservation. Thus, for a more detailed analysis, intrinsic and extrinsic landscape quality is considered:

- Intrinsic quality: this refers to the perception that an observer has, at any point in the territory, from where each unit is visible. It is based on the study of the components of each adjacent territorial sector with a pixel size of 1 meter. The different parameters are then weighted, considering the landscape preference of various authors and consultations with experts in the area [3,37,38]. These studies show that, in general, sites with topographically high and hilly areas are preferable to those with flat surfaces, especially if there is water and vegetation dominates the area, with the presence of trees being more highly valued than scrub. Moreover, landscapes with a high diversity or mosaic structure are valued more highly than those that are monotonous and homogeneous. Five factors are considered for this analysis [12,28]:

1. Geomorphological factor: This is the most relevant factor because the geomorphological domains condition the layout of the relief. Thus, some types of terrain have a more positive landscape assessment (ridges, river valleys, boxed valleys, canyons, escarpments, inselbergs) than others (erosion surfaces, pediments, terraces, sanding zones, floodplain). For the analysis of this factor, it is necessary to weight the following parameters:

    (A) Geomorphological domains: These determine the spatial disposition of the relief units with respect to the adjacent terrain by considering the processes that generate them and grouping them according to morphogenetic systems, i.e., each geomorphological unit is grouped into domains based on the agent that generated them and their associated processes. Table 1 shows the weighting of this parameter.

Table 1. Assessment of geomorphological domains.

Weighting	Geomorphological Domains
10	Fluvial canyon and "sierros"
8	Inselbergs and incised valleys
6	Lomes, valleys, colluviums, and cones of dejection
4	Surfaces and pediments
2	Floodplain, sandy zones, and meanders

    (B) Slopes: These are obtained from the 1-metre DTM, which generates a raster that will subsequently be reclassified into the following intervals (Table 2).

Table 2. Slope assessment.

Weighting	% Slope
0	0–5
2	5–15
4	15–30
6	30–60
8	>60

    (C) Sinuosity: this evaluates the more or less curved nature of the lines of the terrain. An index comparing the area and perimeter of the polygons defined between contour lines has been used for this purpose using GIS techniques [39]. The assessment is shown in Table 3.

Table 3. Sinuosity assessment.

Weighting	Sinuosity
8	Alta
4	Media
0	Baja

2. Lithological factor: Lithology predisposes chromatism in the landscape, which is very decisive when it comes to assessing the intrinsic quality of the natural environment. The color will depend on the different rocky outcrops, with lighter colors being more highly valued than darker ones. In this way, based on the different lithological units

and their relationship with the mineral composition, these units are reclassified in Table 4 into materials with a high percentage of leucocratic or melanocratic minerals:

Table 4. Assessment of lithological chromatism.

Weighting	Lithology
6	Granites, granodiorites, gneisses, and quartz dykes
4	Quartzites and metapelites
2	Slates and shales
0	Conglomerates, pebbles, sands, and clays

3. Hydrological factor: The presence of bodies of water represents an additional value for the nearby natural environment. This refers to watercourses, lagoons, and reservoirs which, in turn, generate a wetland area that can be inhabited by numerous organisms and favor the naturalness of the environment. In this way, the sectors close to watercourses (value 4) and to bodies of water (value 2) are valued. The former are more highly valued because they have a greater perceptual importance in terms of the visual and acoustic senses, as a consequence of the movement of water.
4. Morpho-structural relief factor: This refers to those elements that are singular on a perceptual level and correspond to litho-structural reliefs. These elements are defined by geological structures, such as folds, valleys, and river canyons. The factor is valued at 10.
5. Vegetation factor: Due to the variability of the vegetation, this is a parameter to be considered in the analysis together with the different types of vegetation. To carry it out, two parameters are analyzed:
   (A) Specific composition: this refers to the composition of the various plant associations, characterized by two aspects: plant grouping and diversity. The first is defined as the ecological value of the plant community analyzed, which depends on the dominant species in each plant association, its importance, and also the way in which it conditions the association. Diversity, on the other hand, refers to the fact that the mixture of species reduces the monotony of the landscape and favors the presence of mosaic distributions and particularities of the landscape. The ratings for plant grouping (Table 5) and plant diversity (Table 6) are as follows:

Table 5. Assessment of the plant grouping.

Weighting	Plant Grouping
8	Arboreal postage
6	Shrub
4	Sub-shrub
2	Herbaceous
0	No vegetation

Table 6. Assessment of specific diversity.

Weighting	Specific Diversity
6	More than 3 main species
4	3 main plant species
2	2 main plant species
0	1 or no plant species

   (B) Vegetation structure: This takes into account the presence and distribution of the different elements within each plant association and is defined according to plant density and stratification [40]. Density analyzes the horizontal structure of the vegetation mass and focuses on the amount of vegetation per unit area.

This parameter is assessed in three classes using the Covered Cover Fraction (FCC) (Table 7). The plant stratification, on the other hand, analyzes the vertical structure of the plant elements. In this way, three strata of possible height (herbaceous, shrub, and tree) are differentiated, in addition to the absence of plant strata (Table 8):

Table 7. Plant density assessment.

Weighting	% FCC
4	>40
2	<40
0	0

Table 8. Assessment of plant layering.

Weighting	Plant Layering
6	3 herbaceous + shrub + woody strata
4	2 herbaceous + shrub strata
2	1 herbaceous layer
0	No vegetative layer

To obtain the vegetation valuation cartography, each of the above four parameters is evaluated, reclassified, and superimposed using GIS techniques (map algebra) and applying Equation (1):

$$\sum \text{Vegetation factors} = (\text{Plant grouping}) + (\text{Plant diversity}) + (\text{Covered Cover Fraction}) + (\text{Plant stratification}) \quad (1)$$

Finally, to carry out the total assessment of the intrinsic landscape quality (ILQ), all the above factors were considered. They were superimposed using GIS techniques. By applying Equation (2), we obtained the corresponding cartography:

$$\text{CPI} = \sum \text{Geomorphological factors} + \text{Lithology factor} + \text{Hydrology factor} + \text{Structural relief factor} + \sum \text{Vegetation factors} \quad (2)$$

- Extrinsic quality: This refers to those elements that form the natural and cultural heritage and also to the presence of urban settlements, which add value to the quality of a landscape. In terms of heritage, it is evaluated considering its state of conservation, durability, value (natural and cultural), and social characteristic. In this way, natural heritage includes [12,28]:

(A) Geological heritage: Points of geological interest are considered. All these factors are grouped and weighted with a value of 10.

(B) Biological heritage: This groups plant and faunal heritage together. With regard to biological plant heritage, the areas where there are plant species must be considered by establishing an area of influence of 100 meters and weighting them with a value of 4. The faunistic heritage, on the other hand, groups together the critical areas and points of presence of faunistic species of interest, with an area of influence of 100 m. These, unlike the previous ones, receive a lower weighting (value 2), due to the fact that their presence is more restrictive to the visual field.

(C) Ecological heritage: The different sectors of natural ecological interest are grouped together by considering different criteria: reserve areas, which represent sectors of greater natural quality, weighted with a value of 6; special protection areas for birds (SPAs), which are weighted with a value of 4; and sites of community interest (SCIs), with a value of 2.

With regard to the valuation of the historical and cultural artistic heritage, those constructions and areas of great interest are considered and are subsequently grouped and weighted according to their uniqueness. Thus, the most singular are weighted with a value of 6 (for example, hermitages or churches) and the least singular with a value of 2 (archaeological areas and livestock trails).

On the other hand, the presence of urban settlements with a typology that does not damage the environment is also considered. They are considered as elements that provide recognition to the landscape, such as some of the sites of cultural interest (BIC). Therefore, their presence or absence is valued [41]. Thus, to carry out this assessment, a cartography is generated with the different urban centers, considering a radius of influence of 100 meters. The weighting was carried out in such a way that those sectors that are within the sphere of influence of the population were weighted with a value of 2, while those that are outside were given a value of 0.

Finally, to assess the quality of the landscape, the different thematic coverages were superimposed by considering Equation (3), thus obtaining the final landscape quality map. Intrinsic quality was weighted more highly than extrinsic quality, as it is more noticeable in the landscape [12,18].

$$\text{Landscape Quality} = 0.6 \times \text{Intrinsic Quality} + 0.4 \times \text{Extrinsic Quality} \quad (3)$$

2.4. Cartography of Landscape Fragility

Landscape fragility can be defined as the susceptibility of the landscape to certain human actions or other external impacts by analyzing the response capacity of the natural environment caused by its use. Thus, high landscape fragility is a negative aspect for the landscape because it is highly vulnerable to anthropic action, while low fragility corresponds to those sectors that have suffered less impact, and are valued positively [26,42].

In order to assess landscape fragility, it is necessary to carry out a cartographic analysis of intrinsic and extrinsic fragility to obtain a landscape fragility map. For this purpose, several parameters, such as geomorphology and vegetation, which have already been used to assess landscape quality, have been considered. However, this does not mean that they can affect fragility in the same way [12,28].

Firstly, the factors that determine intrinsic landscape fragility were studied. They are as follows [12,28]:

(A) Geomorphological factor. For the study of this factor, the following aspects have been considered:
   - Slope: The increase in slope raises the susceptibility to human activities, accompanied by changes in the visual aspect of the landscape elements. For example, higher slopes do not favor human activities and the result is higher fragility values. The assessment is the same as that used for intrinsic quality (Table 2).
   - Orientation: Spatial orientation (north, south, east, and west) is an important factor in the calculation of fragility. Thus, the areas of Solana have greater illumination due to the degree of sunshine they receive and present greater fragility than the sectors oriented towards shady areas, which receive less sunshine or less luminosity. Table 9 presents this evaluation:

Table 9. Orientation assessment.

Weighting	Orientation
6	North
4	East
2	West
0	South

(B) Area factor of the landscape units. The larger the area of a landscape unit, the more stable it is, the more difficult it is to modify its characteristics, and the less fragile it is. In order to carry out the analysis of this factor, the cartography of landscape units has been considered to calculate, in hectares, the different areas of each of them.

(C) Vegetation factor. This is responsible for evaluating the following aspects of vegetation:

- Density: A high density of the vegetation mass makes it more stable in the face of possible disturbances, increases its resistance, and decreases the probability of changes caused by external factors. In this way, the lowest densities are those with the highest values of fragility, due to the fact that they are sectors that are easier to modify and that receive a greater impact from external factors. In this case, the procedure to make this map consists of inverting the values of the density map for the quality of the landscape, as discussed above.
- Vegetation stratification: The diversity of strata of the vegetation mass has a direct influence on the analysis of fragility. The highest values of stratification provide the lowest fragility. The assessment is the same as in the case of quality, but with inverted values.
- Area of vegetation units: This refers to perceptual fragility, which increases or decreases with the influence of area and as the perception of impacts on the landscape increases or decreases. Any environmental modification is less perceptible in larger areas, i.e., the larger the area, the lower the fragility of the landscape, giving a value of 0. In the case of areas of greater fragility, the value would be 6.
- Vegetation sinuosity: This refers to the ratio of perimeter^2/vegetation area and allows the effect of this ratio on a vegetation unit to be assessed. Thus, the higher the ratio, the greater the fragility of the landscape, because these areas are more susceptible to possible actions. Its effects are more easily observable, with the valuation shown in Table 10.

Table 10. Assessment of vegetation sinuosity.

Weighting	Fragility of Sinuosity
6	Very High
4	High
2	Low
0	Very low

Once the above factors have been studied and their corresponding cartographies have been drawn up, the cartography of intrinsic landscape fragility (ILF) was obtained from the sum of the cartographies of the above factors, by means of GIS techniques and using Equation (4):

$$\text{ILF} = \text{Geomorphological Fragility Cartography (slopes + orientation)} + \text{Landscape Unit Area Fragility Cartography} + \text{Vegetation Fragility Cartography (density + vegetation unit area + sinuosity)} \quad (4)$$

Then, extrinsic landscape fragility was determined by considering the following factors [12,28]:

- Accessibility: An area is said to be accessible when it is close to an urbanized sector or access infrastructures. Thus, to calculate the areas with greater accessibility, urban centers and roads are considered, to which we apply a zone of influence of 500 m from the point or line of immediate access. In this way, the areas of easy access are those with greater fragility, compared to the sectors farther away from the areas where human concentration is lower or practically non-existent due to the lack of inaccessibility [43].
- Visibility: This can be analyzed through the creation of visual basins, from the DTM. Therefore, the visual incidence of the different human activities and/or natural elements can be determined. In this way, to carry out this analysis, the points of social interest of greater human affluence are considered, as well as the linear coverage of roads.

Once the two previous factors have been studied, the cartography of extrinsic landscape fragility (ELF) is carried out, which is obtained after integrating the cartographies of fragility, accessibility, and visibility and by applying Equation (5).

$$\text{ELF} = \text{Cartography Fragility accessibility} + \text{visibility} \quad (5)$$

Finally, the cartography of landscape fragility (MLF) was obtained by weighting and summing all the layers obtained. Intrinsic fragility is of greater importance because it influences the vegetation physiography and conditions the vulnerability and the capacity to absorb activities that may be installed in each unit of the territory. Extrinsic fragility, on the other hand, is the inverse perception because it intervenes in the perception of an observer located at a point in the environment of one or several specific units. In other words, this concept reflects the potential views of each landscape unit, with less influence than the intrinsic fragility, which indicates what each unit shows. For this purpose, Equation (6) was applied using GIS techniques.

$$\text{MLF} = 0.6 \times \text{Intrinsic Fragility Cartography} + 0.4 \times \text{Extrinsic Fragility Cartography} \quad (6)$$

3. Results

3.1. Cartography of Landscape Units

This cartography (Figure 3) is used to describe the different landscape units by considering the inventory of the different components that make up the landscape and their integration. In this way, different useful maps have been obtained in territorial planning. Once these cartographies were made, the on-site check was carried out, which consisted of direct observation on foot and by car and taking photographs.

Twelve different landscape units were determined in the study area:

Landscapes of fluvial canyons: These constitute one of the most striking landscapes corresponding to the deep incision of the Duero River. They present great scenic value of great naturalness, in an encased space with a scale with a location effect, and with a limitation to the observer with respect to its position, due to the presence of steep walls with a vertical distribution. Two different units can be distinguished:

Fluvial canyons on granite and gneiss rocks with arboreal and sub-shrub formations: The slopes are characterized by rounded shapes with the presence of arboreal formations such as "piorno", together with sub-shrub species such as broom (Figure 4A,B). This unit occupies 1.8% of the total area.

Canyons on metamorphic rocks with tree and sub-shrub formations: The slopes are not as well defined as in the previous case, with the same tree formations (Figure 4C). They have an extension of 1.2%.

Landscapes of incised valleys, colluviums, and cones: These correspond to the incised valleys of the most abundant tributaries of the Duero River (Águeda, Huebra, and Tormes). These are sectors in which the relief is a great protagonism. Landscapes have a great scenic value and a high degree of naturalness. These are closed landscapes due to the existence of abrupt walls that act as visual barriers. Two different units can be distinguished in this landscape:

Boxed valleys with granites and gneisses with arboreal–bush formations. There are rocky outcrops on the slopes and tree formations where the edaphic power is greater, such as mixed formations of holm oaks and juniper, and shrubs such as white broom (*Citysus multiflorus*) or broom (*Genista hystrix*) (Figure 4D). This is a unit with a surface area of 3.4%.

Valleys incised with metamorphic rocks with arboreal–shrub formations and crops, pastures, and fallow land. Unlike the previous ones, they present higher tree density as riparian forests with ash groves (*Fraxinus angustifolia*) (Figure 4E). Their surface area is 2.7%.

Valley landscapes: These correspond to valleys with little incision in the terrain and usually link the surfaces with the valleys that present great incision. Two units can be distinguished:

Valleys with granites and gneisses with arboreal–subarbuscular formations, crops, pastures, and fallows (Figure 4F). This unit occupies 13.9% of the total area. These are open valleys where stream water begins to be channeled over granitic and gneissic lithologies, with scattered groups of arboreal and subarboreal formations with pastures and fallow lands.

Valleys with metamorphic rocks with arboreal–subarbuscular formations, crops, pastures, and fallow land (Figure 4G). These correspond to wide valleys with darker colors than the previous unit as they present metamorphic substrates with groupings of arboreal and subarbustive formations with pastures and fallow lands. This is the unit with the second largest extension, of 14.6%.

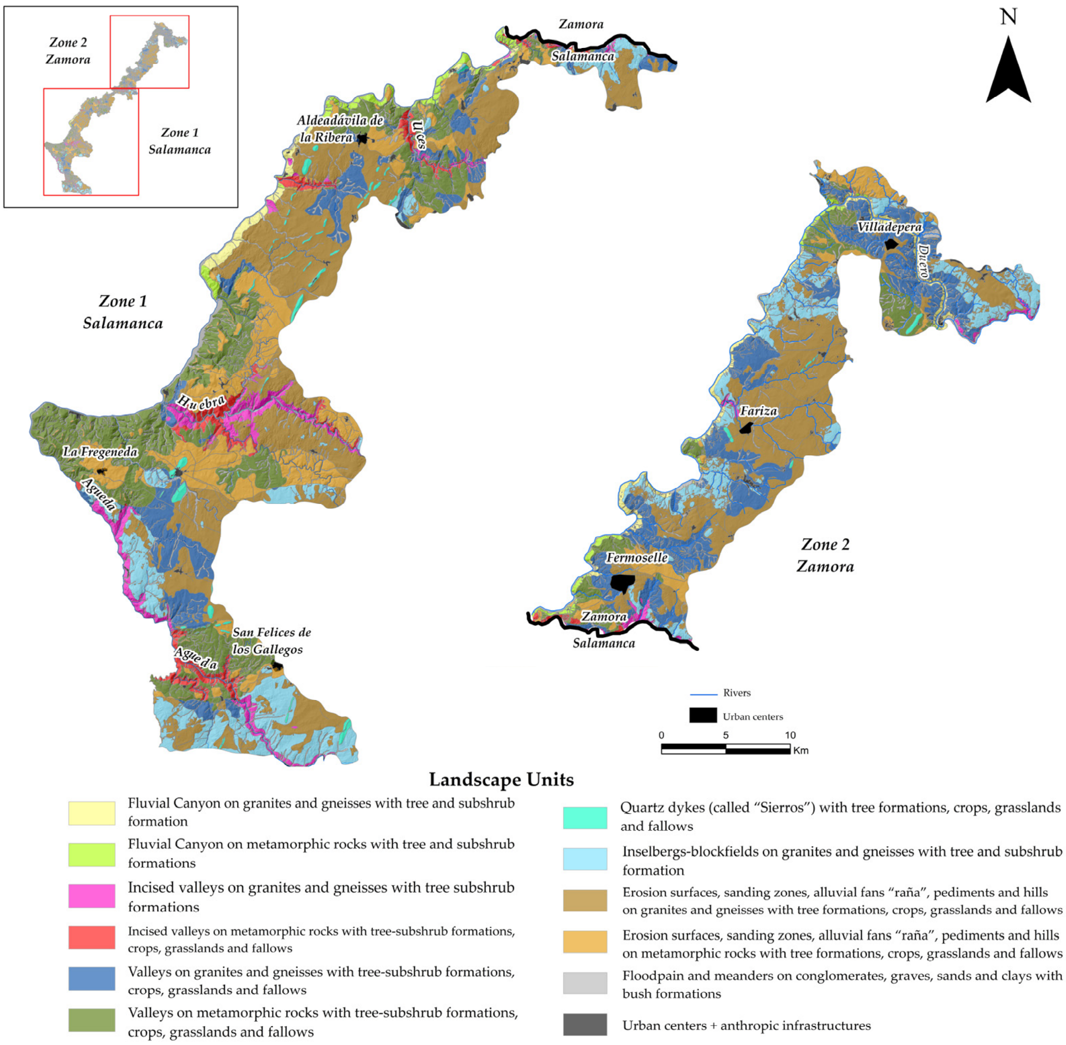

Figure 3. Cartography showing the 12 units that characterize the Arribes del Duero landscapes.

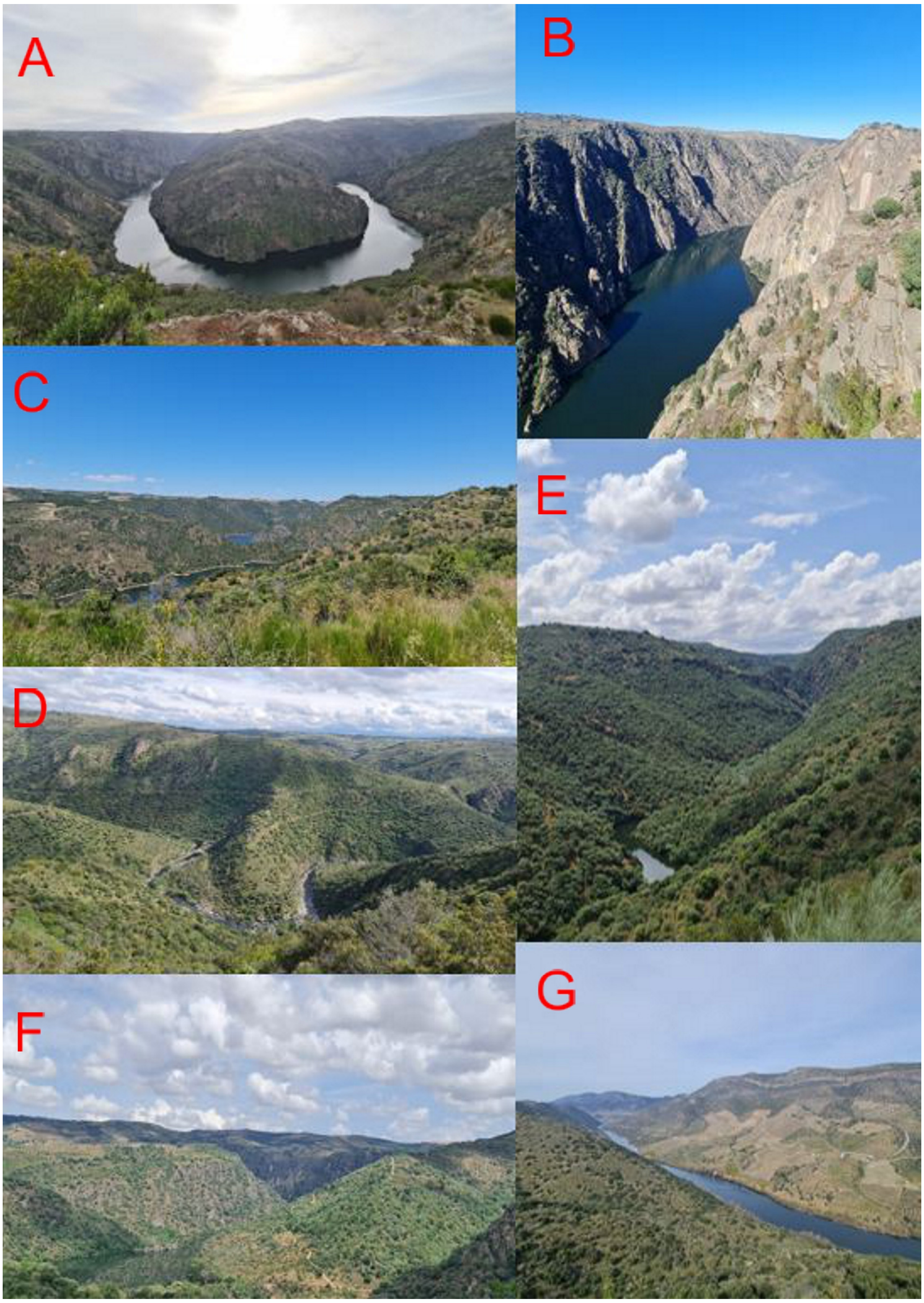

Figure 4. Fluvial canyons over granites and gneisses with arboreal and sybarbustive formations in Fornillos de Fermoselle (**A**) and in the vicinity of the Aldeadávila dam (**B**); fluvial canyons over metamorphic rocks with arboreal and subarbustive formations in Fermoselle (**C**); valleys incised with granites and gneisses with arboreal–sybarbustive formations in the Huebra area (**D**); valleys with metamorphic rocks with arboreal–sub-shrub formations and crops in the Uces river (**E**); valleys with granites and gneisses with arboreal–sub-shrub formations and crops in the vicinity of Fermoselle (**F**); valleys with metamorphic rocks with arboreal–sub-shrub formations and crops in the vicinity of La Fregeneda (**G**).

Landscapes of surfaces, alluvial fans (called "rañas"·), sanding zones, pediments, and hillocks. These correspond to sectors of more or less flat terrain, with hardly any slope and a great amplitude. They present two-dimensional forms, with lines in silhouette, a fine texture, and high contrast. The space is of a panoramic type with a scale that is characterized by a distance effect due to the amplitude of the unit. This is one of the largest landscapes in the study area. Two different units are distinguished:

Surfaces, "rañas", sanding zones, pediments, and hillocks with granites and gneisses with tree formations, crops, pastures, and fallow land. These are located in the surroundings of the valleys and the fluvial canyon, with rounded shapes as a consequence of their lithology and with the presence of arboreal vegetation such as holm oaks (Figure 5A), and some woody crops (mainly fruit trees) and pasture crops in glacis areas (Figure 5B). This is the largest landscape unit, occupying 29.8% of the total area.

Surfaces, "rañas", sanding zones, pediments, and hills with granites and gneisses with tree formations, crops, pastures, and fallow land. These are also located in the surroundings of the valleys, but not in the vicinity of the canyon. They present riparian forests of willow (*Salix salvifolia*) and dry crops, generally cereals (Figure 5C). They occupy an area of 11.1%.

Landscapes of valley bottoms and meanders: These occupy 7.9% of the total surface area. They are constituted by the alluvial valley bottoms of rivers and streams, with conglomerates, pebbles, sands, and clays. These landscapes are linked to the presence of surface water that allows the development of arboreal formations such as riparian forests. The relief has no very vigorous forms, so it does not have much prominence. It presents sectors with a great solid angle that increases its perception, in addition to visual basins of great extension with medium textures. Abandoned meanders are also observed, such as the one of the Saucelle dam (Figure 5D). Finally, another example of these landscapes can be found in the Huebra river, especially at the Molinera bridge (Figure 5E).

Landscapes of inselbergs (Figure 5F,G) and blockfields (Figure 5H). These correspond to large plutonic edifices and more degraded sectors interspersed with saprolites from the sandification of granite that generate, depending on their evolutionary state, different forms such as rocky ground, domatitic forms, and dispersed granitic blocks. They occupy 10.9% of the total area.

They correspond to alignments with a great morphological reflection in the landscape by highlighting quartzite elevations (white colors) on the horizon and in the middle of topographically flatter areas such as surfaces and glacis. This unit occupies the least surface area, i.e., 1% of the total.

3.2. Landscape Quality Cartography

This cartography was obtained from the integration of the components of greatest relevance, uniqueness, and importance. In the detailed analysis, the intrinsic and extrinsic quality were considered.

Intrinsic landscape quality: Based on the cartography of each of the territorial factors considered (Figure 6A–F), the intrinsic quality cartography was obtained (Figure 6G) and classified into five classes from very high to very low quality. Thus, it can be seen that the areas of very high quality correspond to areas of the Duero river, the valleys of the Tormes, Águeda and Huebra rivers, and the inselbergs, i.e., to very localized areas. The high and medium quality areas correspond to valley areas which are sectors with a certain lithological relevance. Finally, the sectors of low and very low quality correspond to erosive surfaces, pediments, sanding zones, and valley bottoms, with a lithology composed of conglomerates, pebbles, sands, and clays.

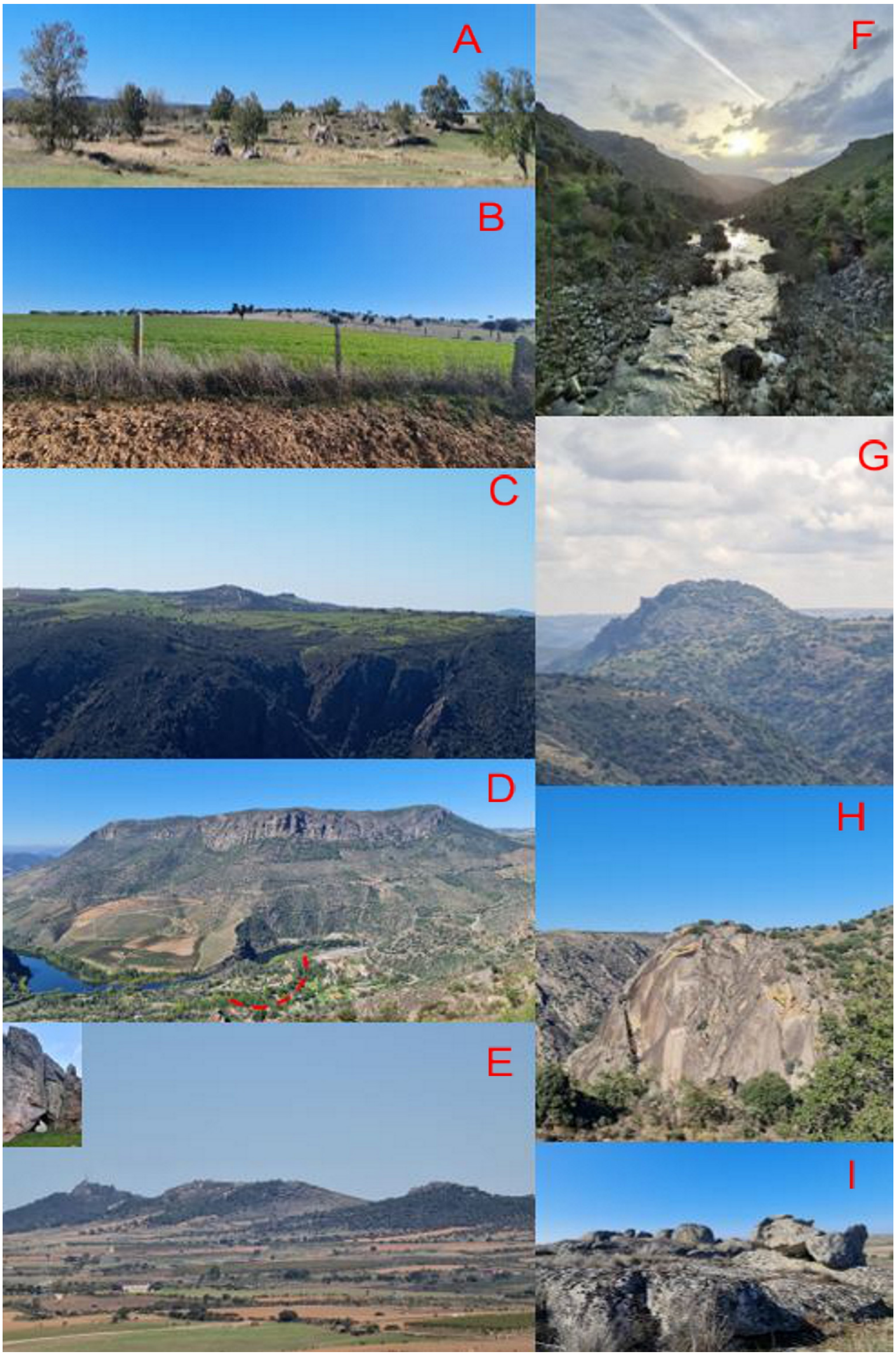

Figure 5. Surfaces, sanding zones, pediments, and blockfields with granites and gneisses with tree formations and crops in the vicinity of Zarza de Pumareda (**A**) and in the vicinity of Hinojosa de Duero (**B**); surfaces, sanding zones, pediments, and blockfields with granites and gneisses with tree formations and crops seen from the Puerto de la Molinera (**C**); abandoned meander in the Saucelle Dam (**D**) and valley bottoms in Huebra river (**F**); inselbergs in Aldeadávila (**G**,**H**) and blockfields (**I**); Sierro in Cerezal de Peñahorcada (**E**); mountain range landscapes (**I**).

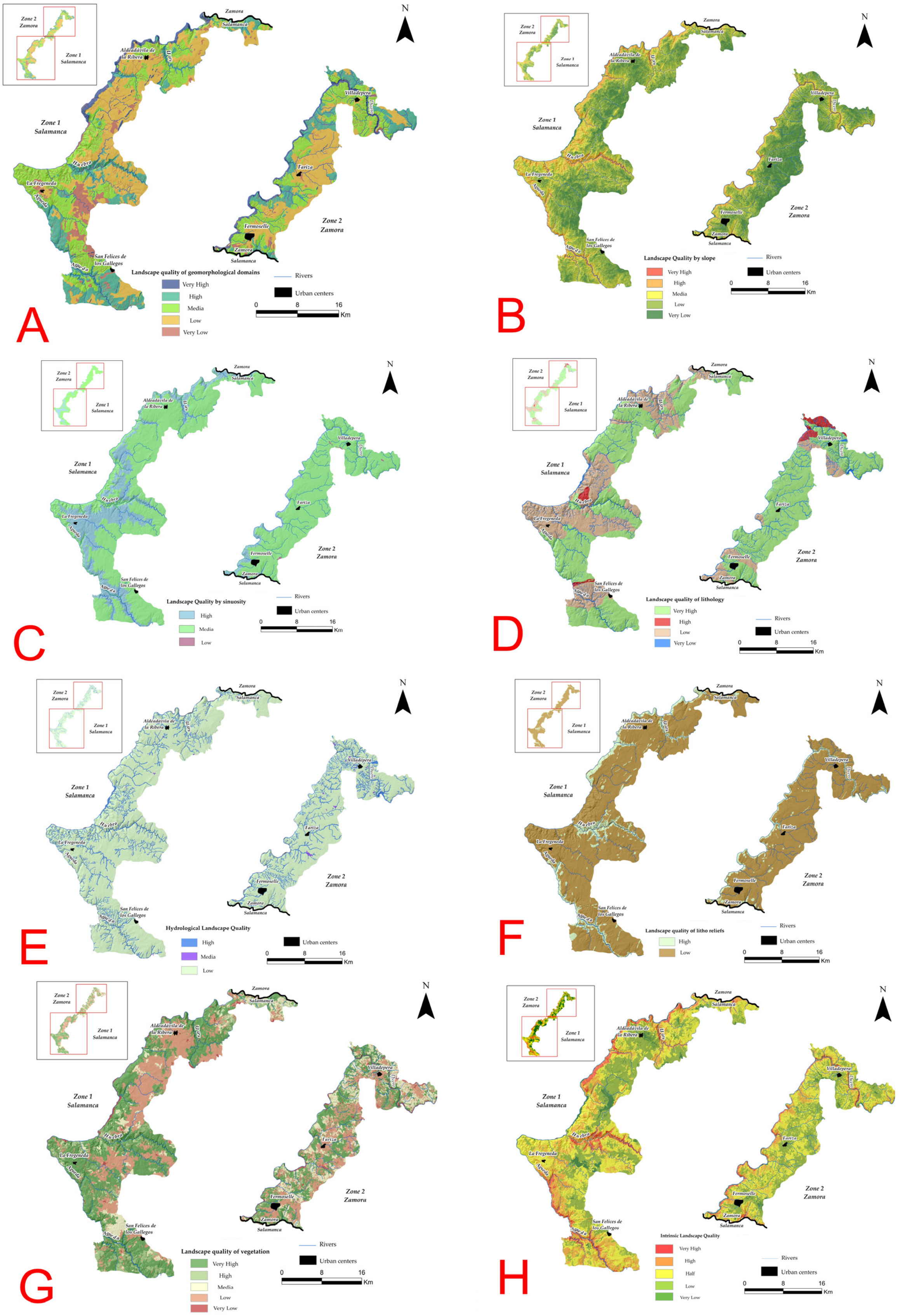

Figure 6. Quality cartographies of intrinsic factors: (**A**) geomorphological units; (**B**) slopes; (**C**) sinuosity; (**D**) lithology; (**E**) hydrology; (**F**) litho-structural reliefs; (**G**) vegetation; (**H**) intrinsic quality.

Extrinsic landscape quality: For its preparation, the cartography of each of the elements of the natural and cultural heritage, as well as the presence of urban settlements (Figure 7A–C), were considered. Like the previous cartography, the extrinsic landscape cartography (Figure 7D) was classified into five classes: the zones of very high, high, and medium extrinsic quality were very specific and coincide in areas where there is some type of protection, such as a special protection area for birds (ZEPA), or due to the existence of urban settlements. The low and very low quality zones are the most extensive, being areas of little interest from the point of view of cultural, biological, and ecological heritage.

Finally, by applying Equation (3), we obtain the cartography of landscape quality, as shown in Figure 8. This cartography shows that the areas of highest quality occupy 26% of the surface area and correspond to hilly areas such as the Duero river canyon and the valleys of the most abundant rivers (Tormes, Águeda, Uces, and Huebra). They are areas considered to be of special protection for fauna and also with flora protection figures (preferential attention, endangered, regulated use, and vulnerable), with the presence of tree formations and mosaic structure. The medium quality is the largest extension, occupying 39%, and corresponds to valley areas and crags with some form of flora protection. Lastly, the lowest landscape quality is 35% and corresponds to areas such as erosive surfaces, with little biological diversity homogeneous structure and without flora and fauna protection.

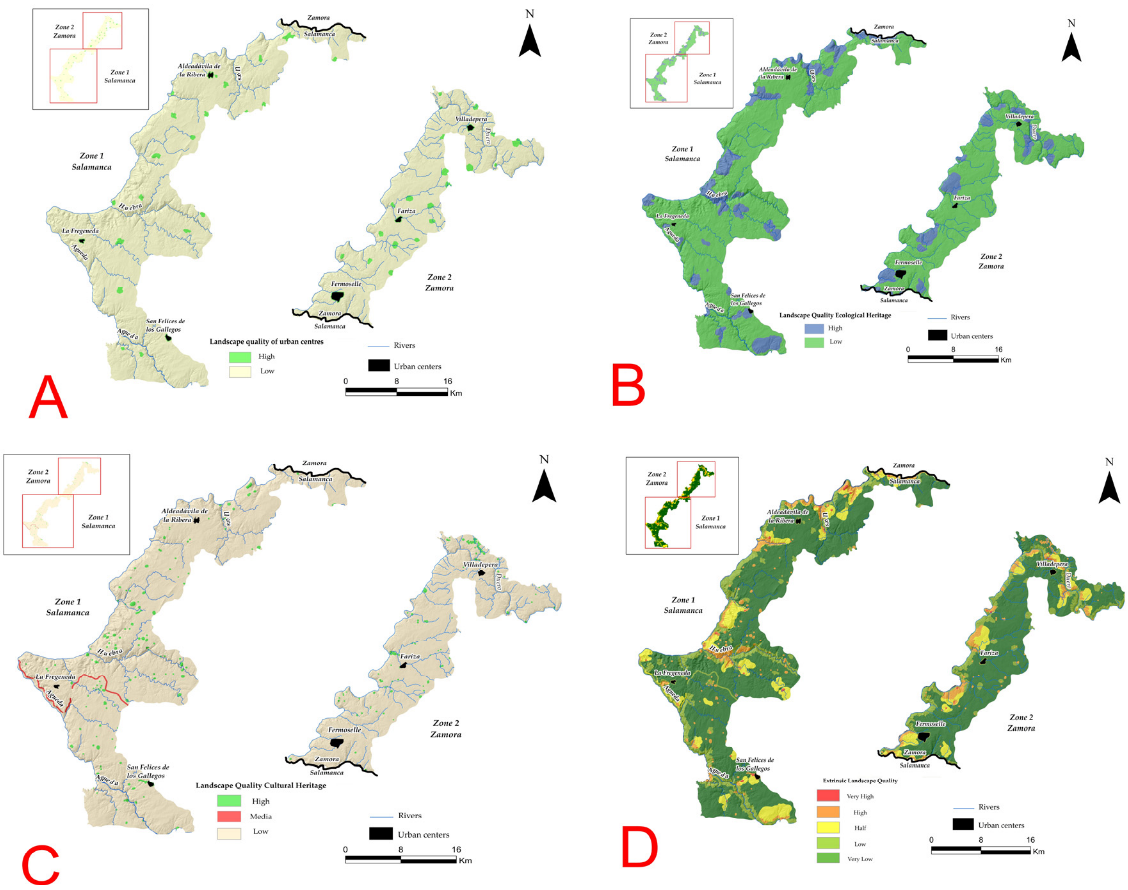

Figure 7. Extrinsic quality cartographies: (**A**) urban centers; (**B**) ecological heritage; (**C**) cultural heritage; (**D**) extrinsic quality.

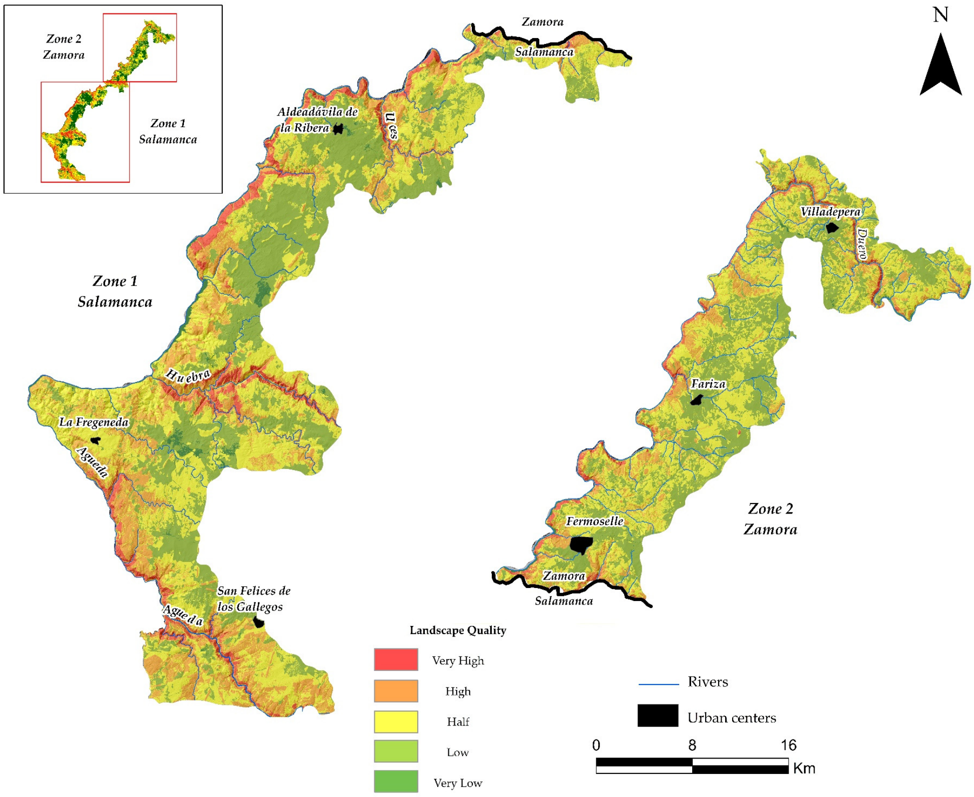

Figure 8. Landscape quality cartography.

3.3. Landscape Fragility Cartography

This cartography was based on the analysis of intrinsic and extrinsic factors, considering several parameters:

Intrinsic landscape fragility: From the integration of the cartographies made of the different factors (Figure 9A–F), the cartography of intrinsic landscape fragility was obtained (Figure 10A). As with the intrinsic quality, the values obtained are classified into five classes according to their degree of fragility (very high to very low). The highest values, i.e., the most fragile zones, were observed in areas of high slope that do not favor the settlement of human activities, such as the fluvial canyon, with a north-east orientation, which constitutes the sunny area and receive greater insolation. With respect to vegetation, these areas are characterized by low density and stratification, due to the fact that they are prone to modification, in addition to receiving a greater impact from external factors. On the other hand, the lowest values were observed in areas with little or no slope, such as erosive surfaces, with a south-west orientation and high stratifications and densities.

Extrinsic landscape fragility: This cartography, like the previous one, was carried out considering the integration of the different extrinsic factors, thereby obtaining a cartography of extrinsic landscape fragility (Figure 10B), classified into five classes. Thus, in the cartography it can be seen that the areas of greatest extrinsic fragility are those with good accessibility, either because of the existence of roads or municipalities, and those with greater visibility of different natural elements (protection areas, points of geological interest, etc.).

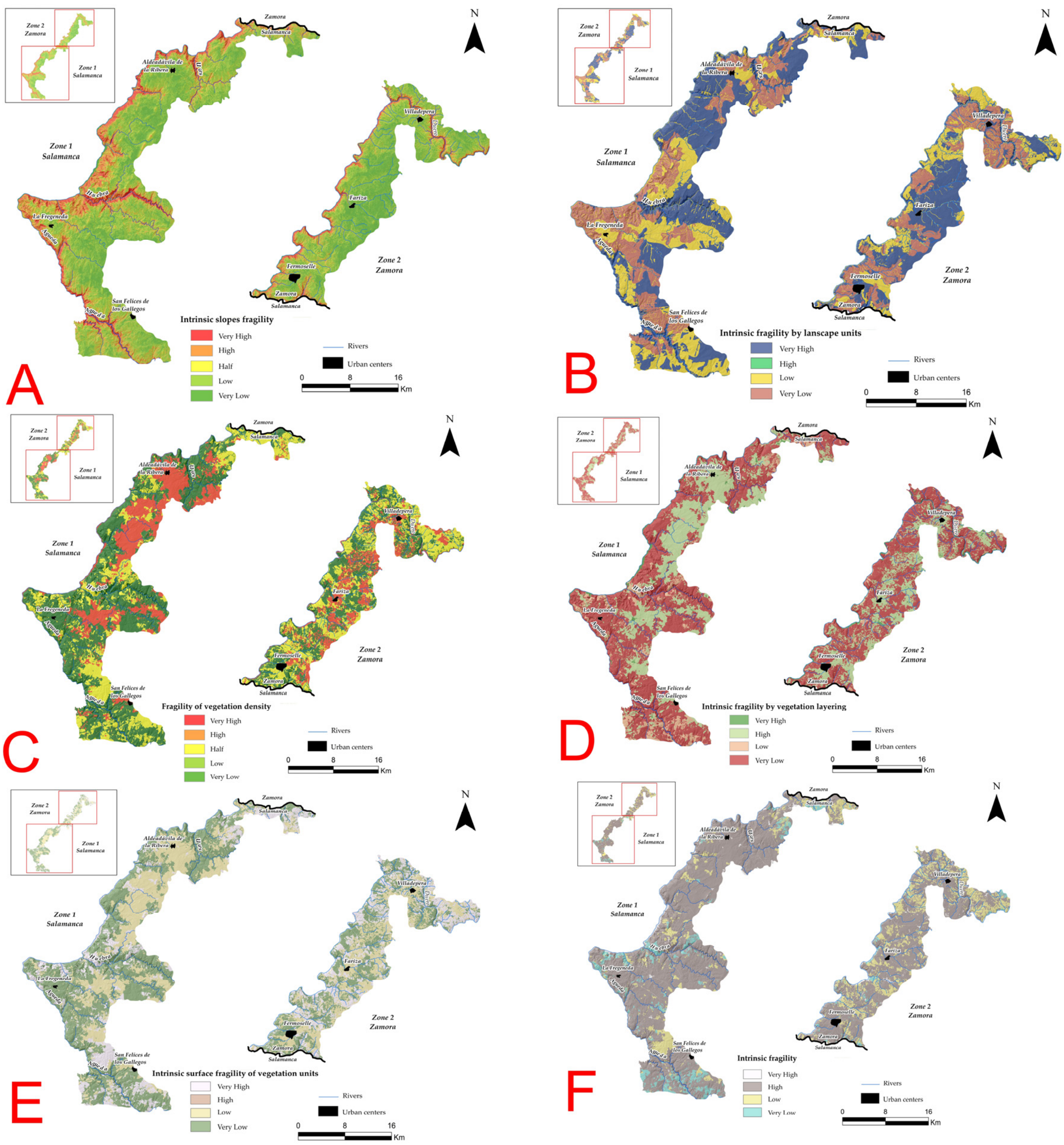

Figure 9. Intrinsic cartographies: (**A**) slopes; (**B**) landscape units; (**C**) FCC; (**D**) plant stratification; (**E**) surface area of plant units; (**F**) sinuosity.

Finally, once the previous cartography was carried out and the equation applied, the cartography of landscape fragility was obtained (Figure 11), with values between 2 and 30 and classified into the five fragility classes. On this map, it can be seen that the areas of greatest fragility are scarce, occupying barely 4% of the surface area, and are concentrated in the outskirts of the municipalities and in the areas of the Duero river basin. The areas of medium fragility are larger than the previous ones, 23%, and are located in surface areas. As for the less fragile areas, they occupy the largest part of the study area, i.e., 73% of the surface area, and correspond to erosive surfaces with crops, trees, or some anthropic activity that give them a greater reception capacity.

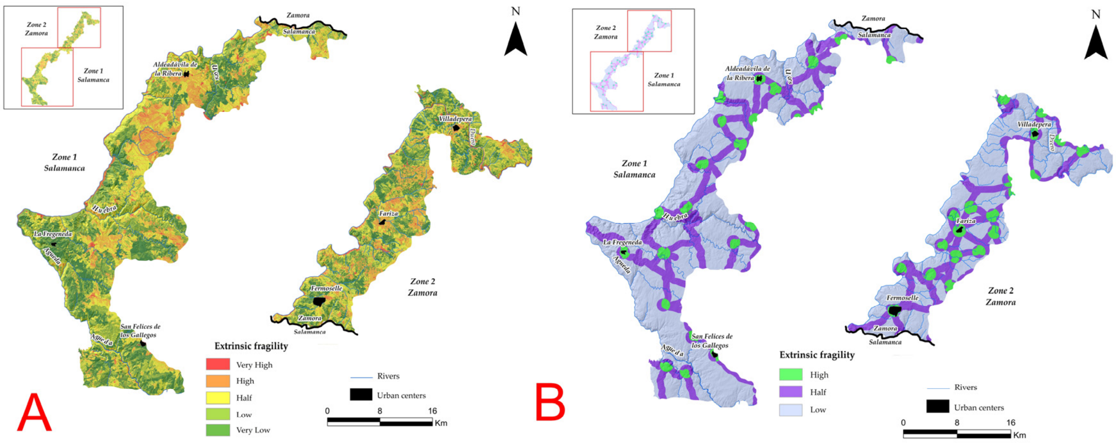

Figure 10. Cartographies of fragility: (**A**) intrinsic; (**B**) extrinsic.

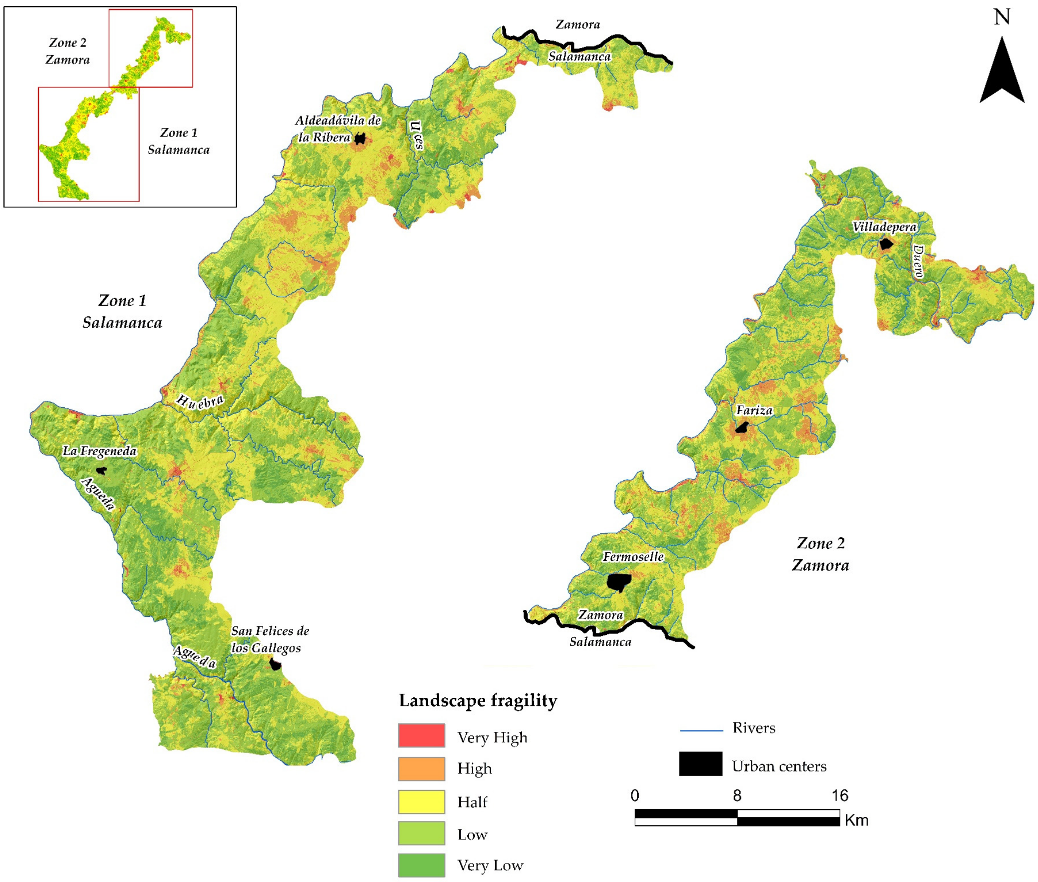

Figure 11. Cartographies of fragility.

4. Discussion

Until now, landscape studies have been considered, for the most part, very subjective because they were conditioned both by the existing environment in each territory and by the psychosocial interests of the observer himself, emphasizing the social, psychological, and economic points of view of the potential observers (urban, rural, religious, ethnographic, etc.). Following the European Landscape Convention, the need to carry out inventories and determine the different landscapes that encompass the singularities of each territory was established, and for this reason, this objective methodology is proposed, based on the creation of geo-referenced and quantifiable cartographies of the different landscape units, based on the natural components of the territory and its singular elements on a smaller scale. In this way, subjectivity is objectified, since the components are measurable and, with the help of GIS techniques, their gain or loss can be measured and assessed in terms of the potential natural capital of possible ecosystem services, since the landscape is a growing resource that is directly involved in the socio-economic environment of a natural space. In this sense, progress is being made in detailed studies of landscape metrics in urban environments or very specific, small areas, or in studies that make it possible, using automatic procedures, to obtain a satellite image to establish the singularities of the area studied.

Our proposal establishes a methodology capable of determining and characterizing territorial landscape units (which to date were simply a physiographic reclassification of the territory according to the different heights of the terrain) that define possible future actions and minimize the vulnerability and environmental impact of anthropic activities or even serve as a tool for prevention in pre-project strategic evaluations.

A landscape analysis is a complex process due to the need to understand the different resources of the physical environment (geology, geomorphology, edaphology, vegetation, etc.), as well as the internal relationships that exist between them. It is therefore a multidisciplinary approach that requires the application of different methods to tackle the complexity of the environment, which converge in a fundamental principle despite their diversity: the territorial reality.

Landscape studies carried out in recent decades have been conducted from two fundamental perspectives: an objective one, which focuses on the evaluation of the natural quality of the landscape, and a subjective one, aimed at appreciating its perception and beauty. As far as this work is concerned, the cartographies generated from these natural resources prioritize geomorphology as a central element in the configuration of the landscape. In addition, these maps synthesize information on lithology and vegetation, reflecting their visual attributes in a comprehensive manner [12,13].

The cartography model implemented in the Arribes del Duero Natural Park constitutes an exhaustive analysis of the resources of the natural environment. The assignment of values is carried out by means of a weighting of different parametric cartographies by considering a multiplicity of criteria and coefficients, which are adjusted according to intrinsic or extrinsic variables. This complexity requires the process to be automatic and leads to the creation of interpretative and synthetic cartographies, based on GIS techniques.

The validation of these cartographies, in order to guarantee their accuracy, was carried out by means of direct methods through direct observation in the field, where different aspects of the landscape were recorded and analyzed. Photographs were also taken. In this way, the landscape units identified in the field through these direct methods are in precise agreement with those obtained by means of the cartography methodology based on indirect methods. This validation, carried out without resorting to GIS techniques, which shows the reliability of the procedure in our study area, as has been evidenced in works that also do not use such techniques [2,6].

The identification of sites of special interest in different areas implies the determination of landscape units with the highest quality and natural beauty for their conservation, knowledge, and protection. This is facilitated by landscape quality cartography, which simplifies the identification of areas requiring conservation measures, especially those with abundant natural resources of great uniqueness and minimal human intervention. The quality cartography obtained shows that the areas of highest quality occupy 26% of the surface area and correspond to hilly areas such as the Duero river canyon and the valleys of the most abundant tributaries of the Duero. The areas of medium quality occupy the largest area, i.e., 39% of the surface area, and are the valleys and crags. As for the areas of lower quality, they cover 35% of the surface and correspond to very regular and flat sectors, such as erosive surfaces.

The analysis of the landscape vulnerability of each zone according to the different land uses requires an analysis of the fragility of the landscape. Landscape fragility is defined as the inverse capacity to absorb alterations without experiencing a decline in quality. The fragility cartography obtained shows that the most fragile areas are scarce and are located in the Duero river basin, coinciding with the areas of highest quality.

Finally, the analysis of the landscape, and its quality and fragility, makes it possible to determine and characterize territorial landscape units which, until now, were simply a physiographic reclassification of the territory according to the different heights of the terrain. This analysis serves to define possible future actions that minimize the vulnerability and environmental impact of anthropic activities or even serve as a tool for prevention in pre-project strategic evaluations.

5. Conclusions

The characterization of homogeneous units identified in the terrain makes it possible to assess the impact and visibility of each one in the natural environment, and thus to establish the quality and fragility of the landscape.

Twelve landscape units were differentiated. They were mapped and identified in the field by direct observation and by analyzing the components and elements of each perceptual unit. This allowed us to analyze of the quality and fragility of the landscape.

In terms of quality, the highest quality areas were found in the areas of the Duero river canyon and the medium quality ones are located in the larger areas. They coincide with the valleys and crags. The areas of lower landscape quality are made up of erosive surfaces, lacking in natural elements that stand out due to the monotony of the peneplain.

In terms of fragility, the areas of greatest landscape fragility are those with the least extension. They are very localized in areas of urban centers and in areas of steep slopes where human settlements are difficult.

Finally, the least fragile areas are the most representative in the area and occupy erosive surfaces with the presence of herbaceous and/or woody crops that give them a greater reception capacity.

The methodology presented is very useful as it provides landscape maps that represent the locations of high quality and fragile landscape areas that need to be protected from human activities, especially in protected areas such as Arribes del Duero. Moreover, it is easily applicable to any place on the planet. It can be used to promote sustainable land management in natural and rural areas, in order to define possible future actions to reduce the vulnerability and environmental impact of anthropogenic activities.

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Article

Water Erosion Risk Analysis in the Arribes del Duero Natural Park (Spain) Using RUSLE and GIS Techniques

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Abstract: Nowadays, soil erosion is a global problem of great environmental and social concern, affecting natural resources, natural spaces and agricultural production. Therefore, it is necessary to carry out an erosion risk analysis to estimate the amount of soil lost, as well as to establish possible conservation practices to mitigate this loss. One way of doing this is through the integration of empirical equations such as RUSLE and GIS techniques, giving rise to a mapping of potential and actual erosion, considering the factors that make up this equation. The results obtained indicate that the areas with extreme erosion levels in Arribes del Duero, that is, with the greatest losses (greater than 200 Tm/ha/year), correspond to areas with steep slopes, poorly developed soils such as Leptosols and Regosols and vegetation with little or no vegetation cover. On the other hand, areas with stable levels of erosion (up to 10 Tm/ha/year) are found in flat areas, with more developed soils, such as Alisols and Luvisols, and vegetation with a higher density and herbaceous cover. Finally, it is concluded that the integration of GIS techniques with parametric equations constitutes a simple and economic tool for estimating these losses and, together with land use, allows different mitigation measures to be established, which, in our study area, focus on reducing the length and gradient of the slope, such as contour cultivation, construction of terraces and "bancales".

Keywords: water erosion; soil loss; RUSLE; GIS; Arribes del Duero

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1. Introduction

Soil loss through erosion is a global problem, affecting natural resources and agricultural production [1–5], and has increased significantly during the 20th century, becoming a global problem of major environmental and social concern [6]. Average soil erosion rates worldwide are estimated to be between 12 and 15 T ha^{-1} yr^{-1} [7], which means that each year, the earth's surface loses about 0.90–0.95 mm of soil [8]. Among the climatic factors causing soil erosion, water is more influential than wind [2].

Water erosion is a natural process involving the separation, transport and sedimentation of materials [9–12]; the main triggers of which are, among others, precipitation, slope and land use changes [13,14]. It constitutes the major form of land degradation, serving as a precursor of irreversible effects on the soil, causing loss of fertility, slope instability and loss of surface horizons [15–17].

Human-induced erosion, on the other hand, is linked to deforestation, poor agricultural practices, overgrazing, forest fires and rapidly increasing urbanisation. The above-mentioned factors, together with other inappropriate land practices, are responsible for triggering erosion along with other inappropriate land management practices [18–20]. In general, these practices can reduce the productive potential of agricultural regions, generate slope instability and reduce soil porosity, which lead to loss of water retention, infiltration and percolation capacity. As a result, surface runoff, sediment transport, siltation and water pollution due to the transport of agrochemicals such as fertilisers and pesticides increase [13,18,19].

Soil erosion may become more severe in the near future due to climate change, further aggravated by increased population pressure, overexploitation of natural resources and poor land and water management practices [20,21]. Soil conservation is needed to reverse the process of land abandonment and improve agricultural production to ensure food security and sustainability. Therefore, there is a need to identify critical areas prone to erosion to provide the necessary information to establish soil conservation strategies, such as protected areas [22].

Researchers have developed different tools to estimate soil loss empirically, such as the Soil and Water Assessment Tool (SWAT), the Water Erosion Prediction Project (WEPP), the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE) [2,23,24]. Among these models, the USLE and its revised version (RUSLE) are the most widely used due to their simplicity, ease of use and ability to successfully integrate the various parameters of the ecosystem or natural areas [25,26]. Therefore, the RUSLE model will be used in this study.

RUSLE is an erosion prediction model, which estimates long-term annual soil loss with acceptable accuracy [27–29]. This model comprises the following five factors: rainfall erosivity (R factor), soil erodibility (K factor), topographic factor (LS factor), land use (C factor) and soil management and conservation practices (P factor) [30,31].

In addition to using empirical equations such as RUSLE in recent years, Geographic Information Systems (GIS) and Remote Sensing (RS) have become useful tools for natural resource management and disaster research. The use of these technologies, which facilitate the handling of many spatial data in a fast and efficient way [32], allows the generation of erosion risk models and cartographies through the analysis of a database to elaborate classifications, map algebra, etc. In this database, it is possible to integrate all the basic thematic parameters (R, K, LS, C and P), resulting in specific mappings, which are overlaid to finally establish synthetic erosive risk mapping [33]. For this reason, many researchers use GIS as the main approach to estimate soil erosion at all scales [34–41].

In this article, which was carried out in the Arribes del Duero natural park (Salamanca-Zamora), the objective is to determine the risk of soil erosion (not previously studied) by using the RUSLE model and, in addition to this, the use of GIS and RS, highlighting as a novelty with respect to other studies the use of satellite images of the highest current relevance and digital terrain models with high spatial resolution, allowing, in a quick way, the development of a cartography of erosion risk in a quick way to distinguish potential and actual erosion. In this natural park, the conservation of soil resources is a priority in order to promote economic activities that lead to population settlement. Finally, this cartography and the land use will determine the possible conservation practices or measures that could be implemented in the future to mitigate these losses.

2. Materials and Methods

2.1. Study Area

The study area (Figure 1) chosen for this work is the Arribes del Duero Natural Space, located to the west of the provinces of Salamanca and Zamora, on the border with Portugal. It is a protected area of 1061 km^2, made up of 38 municipalities and a population of about 17,000 inhabitants. The climate is characterised by mild winters and very hot and long summers in the valley areas, with an average annual temperature and rainfall of 17.1 °C and 500 mm, respectively, in contrast to the extreme continental climate that characterises the plains, with temperatures of 12.2 °C and rainfall of 750 mm [42]. Its landscape is characterised by an undulating peneplain (with a uniform height of 700–800 m) and the steep slopes formed by the canyons (with heights of 130 m) carved by the river system (Duero, Tormes, Uces, Huebra and Águeda rivers). In terms of vegetation, the "peneplain" is a rich mosaic, delimited by stone walls and pastureland, with species of the genus Quercus (holm oak, pyrenean oak, cork oak and gall oak), mixed with other tree species (ash trees) and scrub (scrubland and broom), pastures and dry crops (wheat, barley, rye and vines). For their part, olive and almond trees remain on the slopes and terraces, only displaced by myrtle, holm oak and juniper groves, where agricultural use has been abandoned [43,44]. Finally, it should also be noted that this is one of the areas with the greatest hydroelectric potential in the Iberian Peninsula.

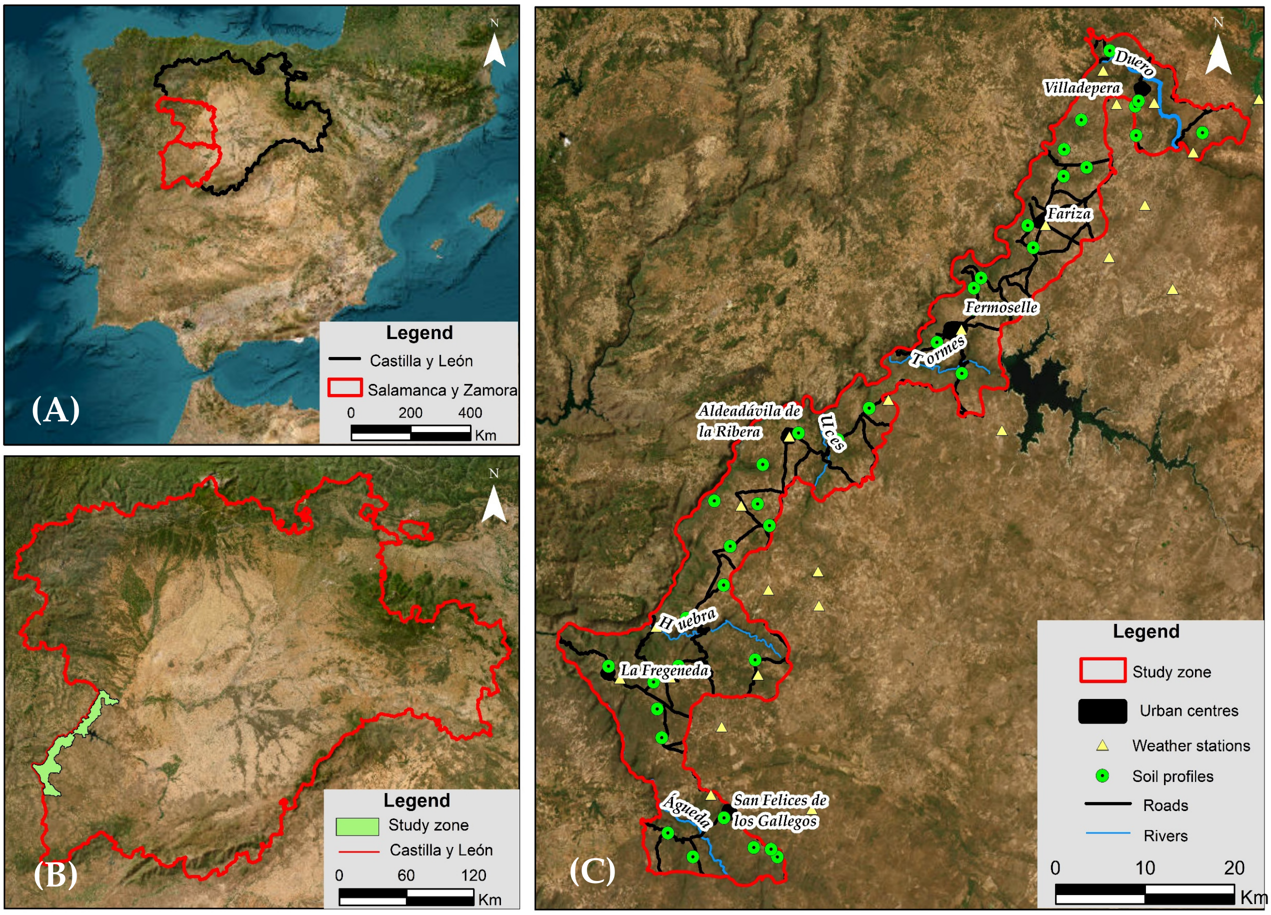

Figure 1. Study area located in: (**A**) Spain; (**B**) Castilla y León. (**C**) Arribes del Duero, highlighting the main villages and rivers, weather stations and soil profiles.

2.2. Methodology

The methodology followed in this article combines field work with laboratory work. As a result, a series of water erosion risk maps of the soils of the Arribes del Duero Natural Park was obtained. The field work focused on obtaining representative samples of the different types of soils existing in the study area. The laboratory work considered of analysing the samples, taking care to establish the necessary parameters for calculating the different factors (granular-metric analysis, organic matter, structure, etc.) that determine the application of the RUSLE to the risk of water erosion. Finally, the data obtained in the field campaigns and the laboratory analyses were studied by applying graphic (Wischmeier nomogram, DTM generation, etc.) and empirical procedures (formulas for the calculation of parameters, RUSLE equation, etc.), in order to elaborate a database that has been implemented in a Geographic Information System (ArcGis 10.5) and to obtain different parametric and final erosion risk cartographies of the study area.

Therefore, the quantification of soil losses due to water erosion has been carried out by means of two mappings (Figure 2) [45].

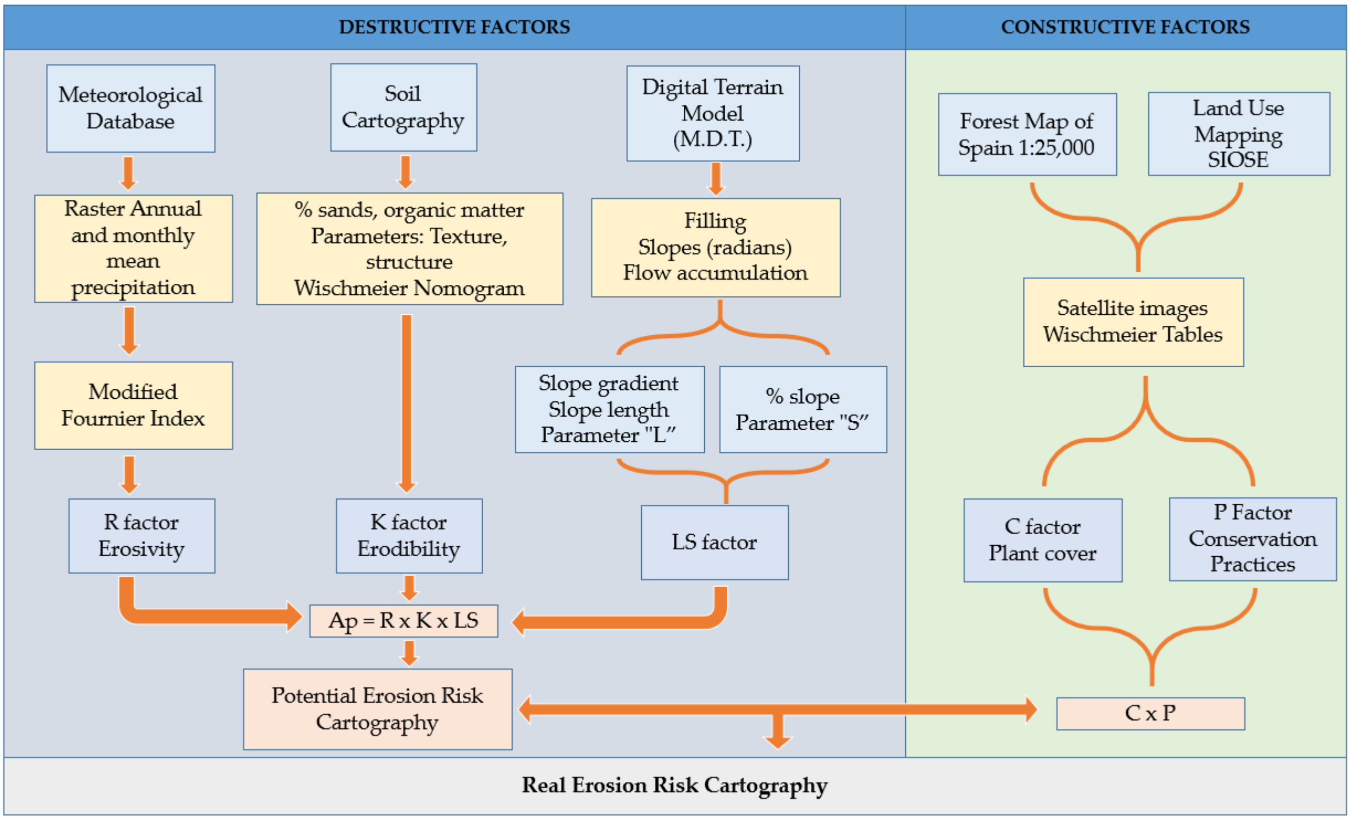

Figure 2. Methodological scheme for mapping water erosion risks in the Arribes del Duero Natural Park.

1. Map of Potential Erosion or states of the terrain under hypothetical natural conditions: this constitutes the susceptibility of an area to erosion. In order to predict this risk, a detailed study of a series of factors or elements of the physical environment (mechanical resistance, rainfall, slopes, etc.) that condition erosion processes is performed. Knowing these variables, the potential erosion units can be inventoried and mapped by using erodibility indices (lithofacies and slopes) and erosivity indices (aggressiveness of rain).

2. Current Erosion Map: it considers current conditions and determines the degree of current soil loss in each area by considering the "present moment" and analysing the soil forming and protective factors, as well as its spatial distribution (types of crops and native vegetation and conservation practices).

For both mappings, the modified version of the RUSLE has been used to estimate the average annual soil loss under different conditions of use, climatic variation, relief and use of conservation practices. This model is expressed by Equation (1):

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the soil loss per unit area in a given time in Tm/ha/year, R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the topographic factor encompassing slope length (L) and slope steepness (S), C is the land use and management factor and P is the soil conservation practices factor.

2.3. Potential Erosion Risk Cartography

The Potential Erosion Map is obtained from the multiplication of the three factors R, K and LS. Once obtained, the reclassification of the erosive degrees is carried out in smaller intervals, using the criteria in Table 1.

Table 1. Annual soil loss classification.

Types of Erosion	Loss of Soil (Tm/ha/year)
Very low erosion and tolerable soil loss	<5
Low erosion and tolerable soil losses	5.1–10
Mild erosion level	10.1–25
Moderate erosion level	25.1–50
Severe erosion level	50.1–100
Very severe erosion level	100.1–200
Extreme erosive level	>200

2.3.1. Rain Erosivity Factor (R)

This factor considers the average of the kinetic energy intensity values estimated from monthly and annual average rainfall [12]. This rainfall must have a continuous record of rainfall intensity variations and has been obtained from the database of the Geographic Information System for Agricultural Data (SIGA) [46].

To obtain this factor, firstly, rainfall data were collected from 35 stations in the study area, with data from more than 20 consecutive years. Then, given the dispersion of the stations, an interpolation was carried out using the weighted distance method (IDW) with ArcGis. In our study, we have worked with a cell size of 5 metres, thus obtaining greater precision. This operation was repeated each of the month of the year, thus obtaining the corresponding raster. The next step was the application of the Modified Fourier Index (IMF) [47], whose formula is (2):

$$IMF = \Sigma_{i=1}^{12} \frac{p_i^2}{Pt} \quad (2)$$

where p_i is the precipitation of each month in mm and Pt is the mean annual precipitation in mm. Each of the previous raster corresponds to each of the 12 values of p_i, so that from them we can obtain the raster that represents the value of the mean annual precipitation, which will be the sum of all the monthly precipitation values. Finally, to calculate the R Factor, we have used Equation (3), which is the regression equation proposed by the I.C.O.N.A. for the region where our study area is located, which allowed us to calculate the value of R as a function of readily available precipitation variables, such as the total precipitation or maximum precipitation in a month [48]:

$$R = 2.56 \times IMF^{1.065} \quad (3)$$

2.3.2. Soil Erodibility Factor (K)

This is a sensitive parameter related to regional characteristics, soil structure and degree of weathering. It describes the susceptibility of the soil to detachment and transport of particles in quantity and flow rate for a specific predicted rainfall event. It is a quantitative value experimentally determined from soil texture, structure, organic matter content and permeability [10,12].

This factor is obtained using with the data obtained in the physico-chemical analyses carried out in the laboratory of the 38 soil profiles taken in the field work, necessary for the use of the corresponding Equation (4), whose values are shown in Table 2. The values obtained have been validated with the Wischmeier nomogram [12].

$$100K = \left[10^{-4} \times 2.71 \times T^{1.14} \times (12 - MO)\right] + 4.2 \times (E - 2) + 3.2 \times (P - 3) \quad (4)$$

where T is the texture parameter of the surface 15 cm, MO is the organic matter content (%), E is the structure and P is the permeability.

Table 2. Erodibility values.

Soil Type	K Value
Gleyc luvisols	0.12
Chromic alisols	0.17
Chromic cambisols	0.19
Dystric gleysols	0.20
Eutric cambisols	0.22
Dystric cambisols	0.24
Eutric regosols	0.28
Dystric regosols	0.38
Dystric leptosols	0.39
Lithic leptosols	0.49

2.3.3. Topographic Factor (LS)

The topographic factor is determined by the length of the slope (L) and the slope (S). Thus, it establishes the need for an exhaustive knowledge of the spatial distribution, since soil erosion is intensified as a consequence of the concentration of runoff water towards the lower areas. As L increases, soil erosion increases, as well as increasing as a consequence of velocity and surface runoff [12].

To calculate this factor, the methodology followed by Zhanh et al., 2013 [49] was used, based on Equation (5), proposed by Moore and Burch (1986) [50]:

$$LS = \left(Flow\ accumulaion \times cell\frac{size}{22.14}\right)^{0.14} \times \left(\frac{sinslope}{0.0896}\right)^{1.3} \quad (5)$$

where Flow Accumulation is the number of cells contributing to the flow in a given cell, cell size is the length of the size of one side of the cells and sin slope is the sine of the slope in radians.

First, the slope is calculated in degrees and then transformed to radians. Next, the calculation of the slope length is carried out, which is done on the basis of the flow accumulation raster, which represents the cells in which water accumulates when flowing from the cells with the highest altitude value. To obtain it, it is necessary to calculate the filling of sinkholes, the flow directions and the accumulation of flow. Once the slope and slope length are obtained, the LS Factor is calculated considering the above formula, which involves multiplying the flow accumulation by the cell size. In our study, the maximum flow accumulation value is 4796.821, which multiplied by the cell size (5 m) would result in a high maximum runoff length. Therefore, using these data would be erroneous, as it would overestimate the value of the slope length, resulting in exaggerated erosion values. To avoid this, it is necessary to establish a maximum length of 25 m, which is equivalent to 5 cells, thus obtaining a flow accumulation raster with a maximum value of 5. Finally, a reclassification of the flow accumulation is carried out (considering this maximum length), which will be used to calculate the LS Factor by means of the above formula.

2.4. Real Erosion Risk Cartography

This cartography is obtained from the Potential Erosion Map by adding two terms from the RUSLE, which are: the crop or vegetation factor (C-factor) and the Conservation Practices Factor (P-Factor).

2.4.1. Plant Cover Factor (C)

This factor analyses the influence of plant species, crop rotation and the degree of erosive susceptibility of the soil, which will influence its productivity. For its calculation, the management of plant masses and crops is considered, using the Forestry Map of Spain, scale 1:25,000, delimiting the study area. Finally, to obtain this value (Table 3), the values established for tree, shrub and mixed tree formations are considered, analysing the percentage of tree and shrub cover, type of herbaceous cover and thickness of plant debris as well as its extent [22]. For the herbaceous formations, the Wischmeier classification was considered [51]

Table 3. Vegetation Cover Values.

Vegetation Cover Type	C Value
Mixed hardwood forests	0.003
Mediterranean scrub	0.04
Riparian forest	0.09
Poplar and banana plantations in production	0.09
Ash groves	0.09
Wild olive groves	0.18
Juniper groves	0.18
Cork oak groves	0.19
Meadows	0.19
Holm oak groves	0.19
Oak groves	0.19
Chestnut groves	0.22
Non wooded	0.24
Mixed conifers	0.42

2.4.2. Soil Conservation Practices Factor (P)

This factor analyses the existence of soil conservation practices in land use [27]. In this study, as in most soil loss estimates, it is not considered, given that we are interested in knowing the potential and real losses considering natural factors. On the other hand, human activities can increase this soil loss or reduce it through the implementation of specific actions: terraces and contour cultivation. As a result, this is a parameter to be subtracted from the potential erosion risk, so it is not considered, i.e., Factor P in our study area has a value of 1 [44].

3. Results and Discussions

The USLE factors (Figure 3), have been estimated with a 5 m × 5 m grid, being a very precise scale that allows us to provide the special distribution of the average annual soil erosion in the Arribes del Duero Natural Park with great detail and to resemble reality as much reality as possible, unlike other grids of lower precision.

3.1. RUSLE Factor Analysis

The R Factor has been obtained from the monthly and annual rainfall data of the different meteorological stations spread over the study area with normal data (20 years) by applying the IMF. Average annual rainfall ranged between 483.9 and 846.4 mm. The highest rainfall was concentrated between Saucelle and Aldeadávila. This factor shows values ranging between 156 and 291 (Figure 3A), being maximum between the above-mentioned localities.

The K factor has considered the soils studied by the authors in previous works, as well as their corresponding physico-chemical data [52]. With these data and the Wischmeier nomogram, values between 0.12 and 0.49 have been obtained (Figure 3B).

The topographic factor is influenced both by the length of the slope and by the gradient; therefore, geomorphological aspects are one of the main factors that determine the emission of sediments in a river basin. Our study area is characterised by the boxing in of the Duero River, i.e., a peneplain followed by a steep slope, the latter being more susceptible to erosion. Observing the results obtained (Figure 3C), the values range between 0 and 61. The areas with the steepest slope and the longest slope have the highest values.

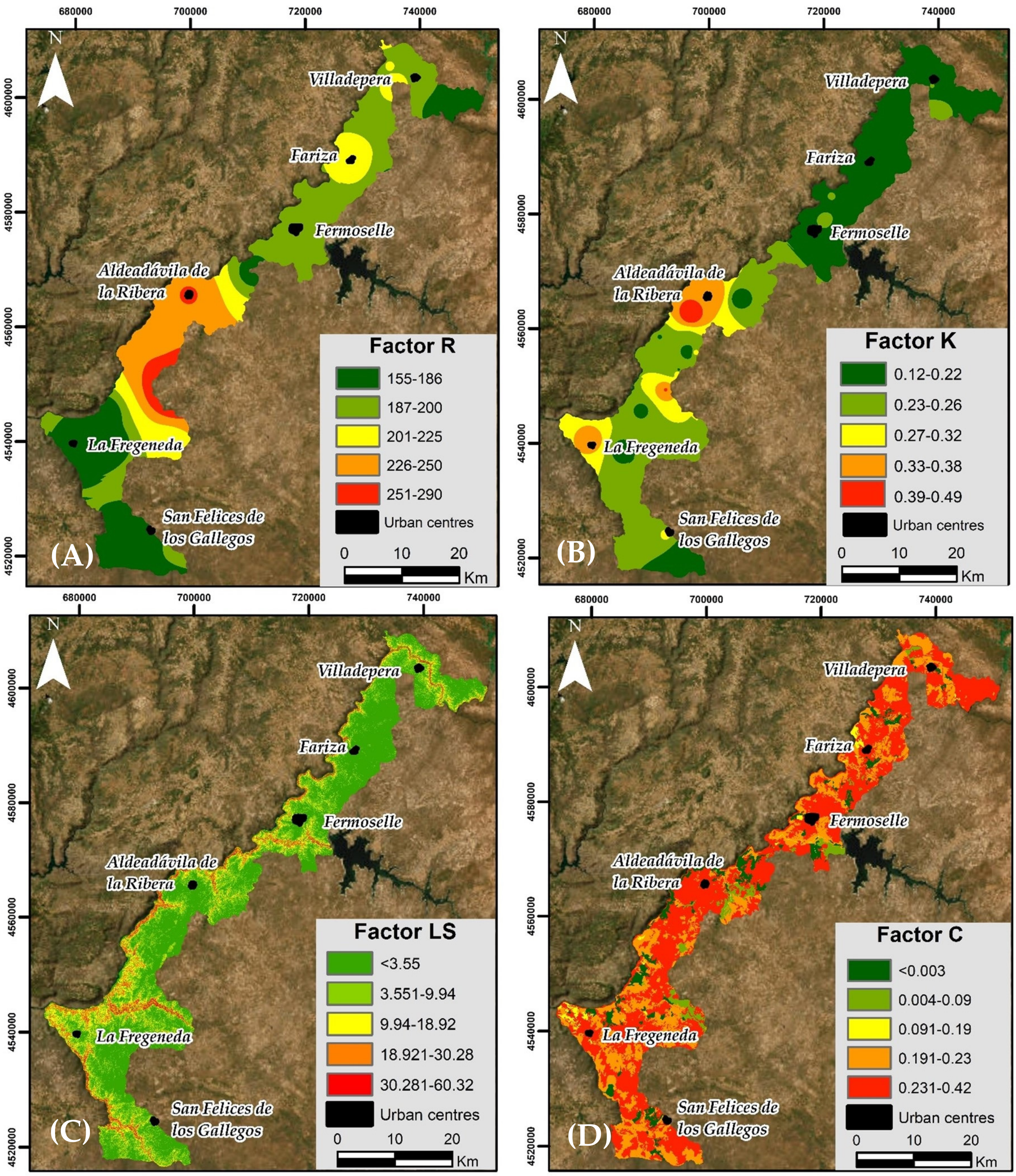

Figure 3. USLE factors: (**A**) Rainfall Erosivity Factor (R); (**B**) Soil Erodibility Factor (K); (**C**) Topographic Factor (LS); (**D**) Vegetation Cover Factor (C).

Finally, the vegetation cover factor (Factor C) is a determining natural element in the protection of the soil against the erosive force of precipitation, because in addition to controlling the energy with which raindrops hit the surface of the soil, it slows down the speed of surface runoff. Additionally, stoniness must be considered because it acts as protection, reducing the inertia with which the drops fall, since the soil is covered by fragments of rock or gravel. In view of the results obtained (Figure 3D), C values between 0.003 and 0.42 are obtained.

3.2. Potential Erosion Risk Cartography

To make this mapping (Figure 4), the factors of the physical environment have been multiplied: R, K and LS, showing the susceptibility of the area to erosion, considering the existing conditions. In this way, the areas corresponding to the Duero River basin, as well as its main tributaries such as the Tormes, Águeda, Huebra and Uces, are where the greatest erosion is identified, with values of over 200 Tm/ha/year (reaching 5137.36 Tm/ha/year), being identified as an extreme erosive level.

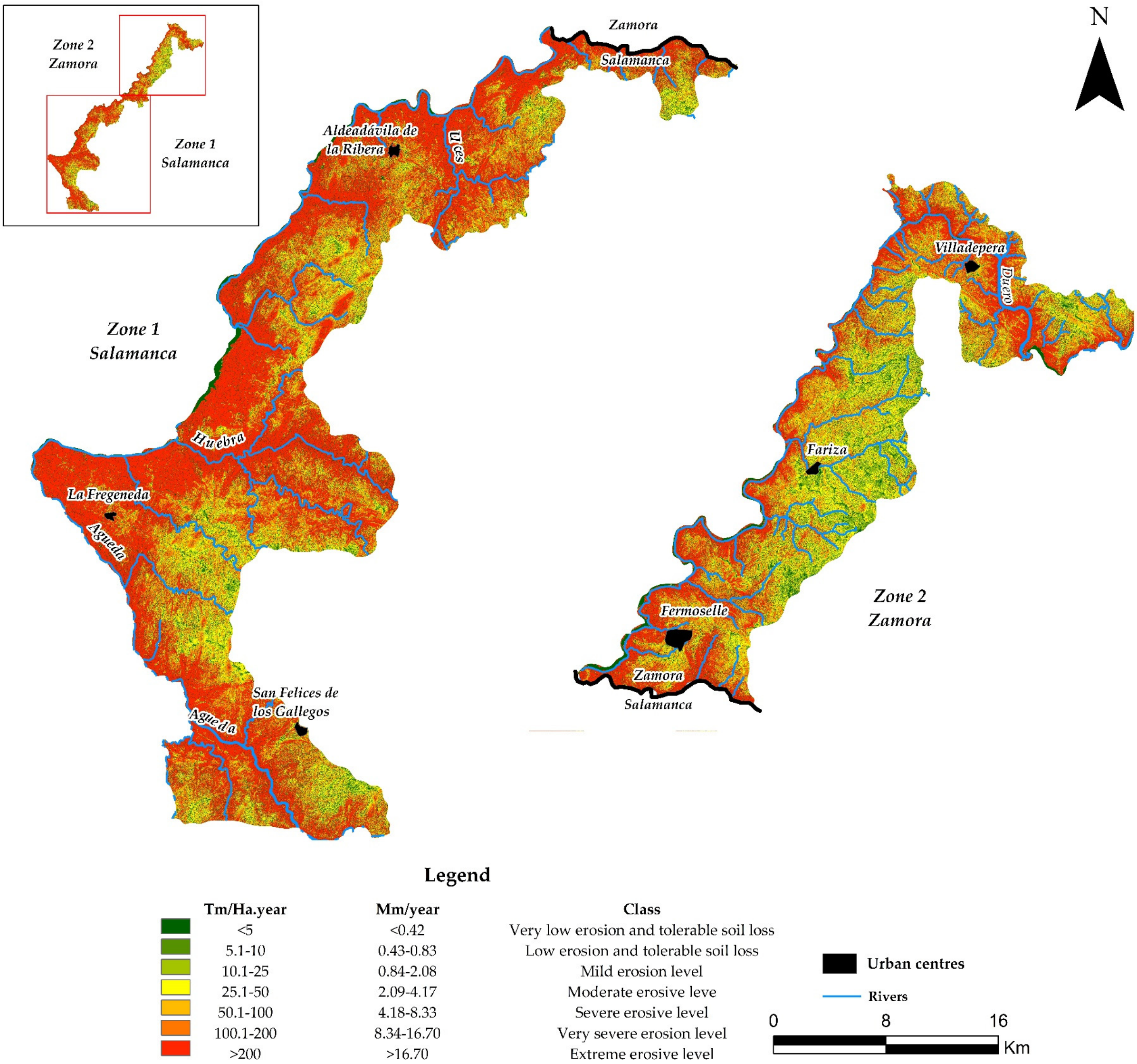

Figure 4. Potential Erosion Map. Zone 1: province of Salamanca; Zona 2: province of Zamora.

This area coincides with high slopes that favour turbulent movements, giving rise to severe erosive forms, such as rills (Figure 5A) and gullies (Figure 5B), and, in addition, with poorly developed soils, such as Leptosols and Regosols, which have a higher sand content that act as erosive agents as it is dragged along by surface runoff. There are differences between these soils: the lithic and distric Leptosols are more susceptible than the Eutrophic regosols. The former because they have an A horizon with little thickness (<10 cm); the latter because they are desaturated. The clays are more susceptible to dispersion, compared to the Eutrophic regosols, which are saturated. On the other hand, the areas with a moderate and medium level of erosion, with values between 10.1 and 50 Tm/ha/year, correspond to peneplain areas in which medium development soils predominate, such as Gleysols and

Distric and Eutric cambisols, which, unlike the previous ones, have a cambic. Among them, the Distric cambisols are the most susceptible as they are desaturated, compared to the Eutric cambisols and the Distric gleysols. Finally, the tolerable levels of erosion (up to 10 Tm/ha/year) are also found in peneplain areas, with the difference that the soils are more developed, such as Chromic cambisols, Gleyic luvisols and Chromic alisols. These soils are characterised by a higher content of dehydrated iron oxides, which act as a bridge between the clay and the organic matter, giving this complex greater stability to the soil. The other two types of soil are characterised by a Bt horizon of clay illuviation, i.e., with a higher percentage of clay, and also have a higher organic matter content with a more developed clay-humic complex, which protects the soil from possible erosion.

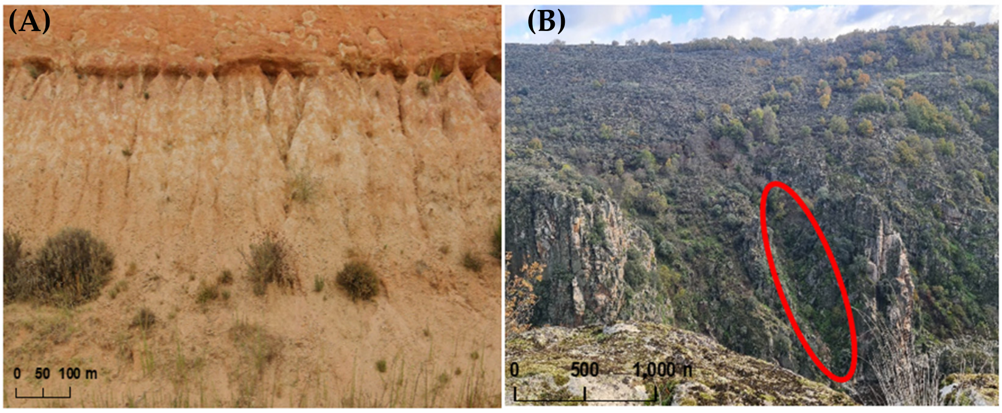

Figure 5. Erosional forms observed: (**A**) Rills; (**B**) Gullies.

3.3. Real Erosion Risk Cartography

This map indicates the current erosion risk (Figure 6). It has been drawn up on the basis of the potential erosion risk considering the vegetation cover factor, which gives the soil certain protection, depending on its characteristics (height, density, percentage of cover and territorial extension). In order to classify the degrees of water erosion obtained, a reclassification is carried out considering the aforementioned criteria, expressed in Tm/ha/year and mm/year.

In view of the results, the areas suffering the greatest water erosion are those located in the river beds, especially in the case of the Duero River and its most abundant tributaries. These sectors are characterised by their steep slopes, increasing the speed of surface runoff as it descends, thus carrying away the materials most susceptible to erosion. In addition to this, it coincides with areas of vegetation with little protective power and with low percentages of cover, such as conifers and broadleaf trees, which further accentuates the erosive vulnerability of these soils. These areas show severe to extreme erosion, with values ranging from 50.1 to >200 Tm/ha/year and soil losses ranging from 4.18 to >16.70 mm/year. On the other hand, we find lower erosion values in the plain areas (<4.18 mm/year), as there are no or little slopes and the characteristic vegetation provides greater protection. It has a greater density and herbaceous cover and makes this area less vulnerable to erosion.

3.4. Erosion Validation and Mitigation: Land Uses Erosion

For the validation of erosion, the real erosion cartography and the land use map (SIOSE) have been considered, making it possible to determine the uses most susceptible to erosion in order to establish possible conservation practices to mitigate these losses. Thus, the most affected uses, ordered from highest to lowest, are as follows (Figure 7): coniferous and hardwood forests, crops, olive trees, non-citrus fruit trees and scrubland. In the case of coniferous forests, the needles tend to acidify the ground when they fall, preventing the development of herbaceous plants and leaving on the ground bare and exposed to runoff.

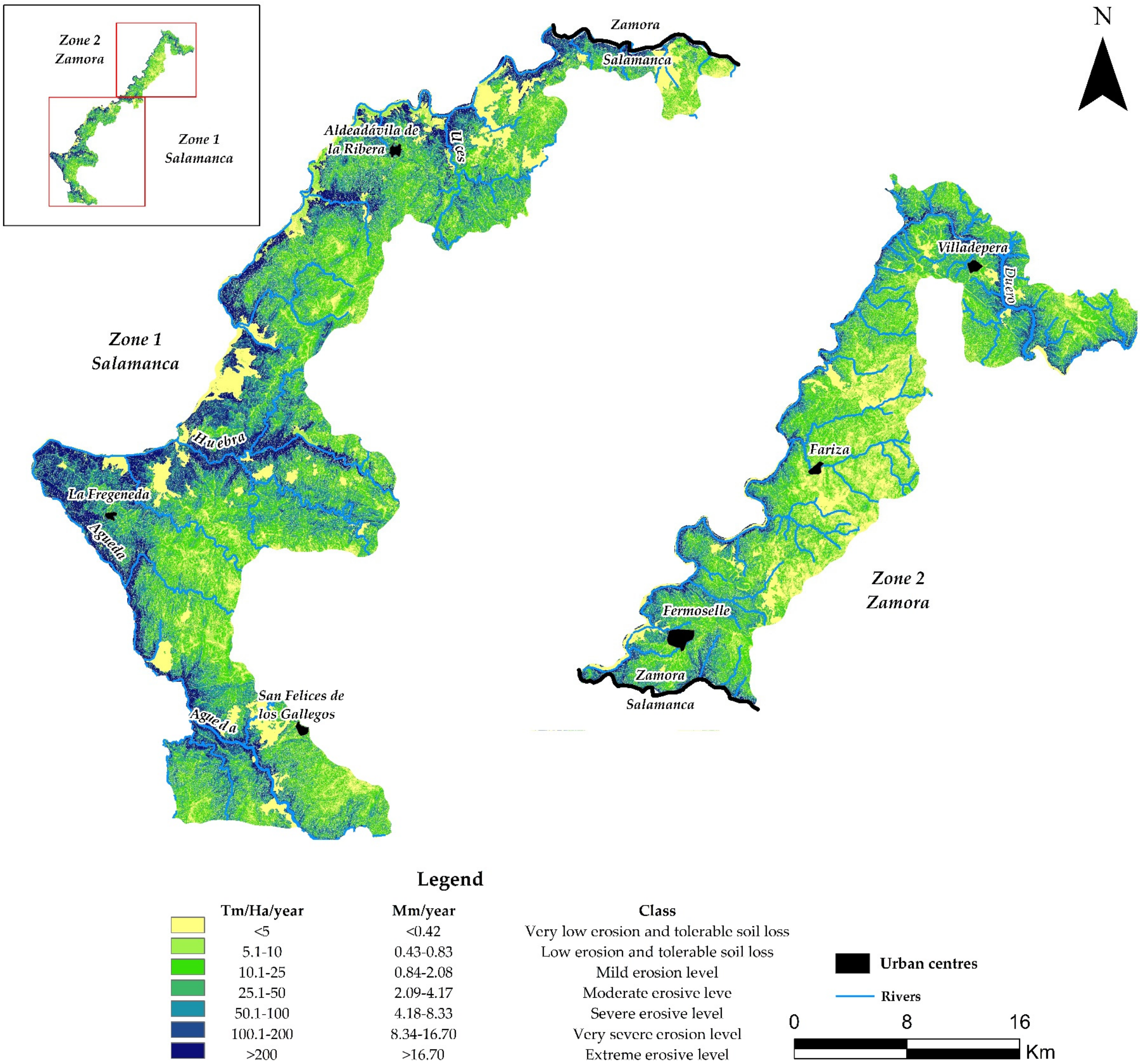

Figure 6. Real Erosion Map. Zone 1: province of Salamanca; Zona 2: province of Zamora.

The hardwood forests characteristic of the study area does not have an appreciable undergrowth and, therefore, leave the soil exposed to erosion. Both olive trees and non-citrus fruit trees have a very low percentage of cover with hardly any protection for the soil. Lastly but to a lesser extent, scrubland, varies according to its density; if it is denser, it will provide greater protection to the soil.

Bearing this in mind and considering that the most affected areas have a steep slope, the practices that can be carried out are: reducing their length (and thus, the speed of runoff) and breaking up the slope. Some examples of such practices are contour cultivation (following contour lines), construction of "bancales" (Figure 8A) or terraces (Figure 8B), among others. The latter have already been carried out in the area, especially with vine crops. As they do not require highly developed soils they are adapted to this type of practice. Therefore, the use of this crop and this practice is very useful for reducing erosion in these areas where the soils are not very developed and the slope is steep.

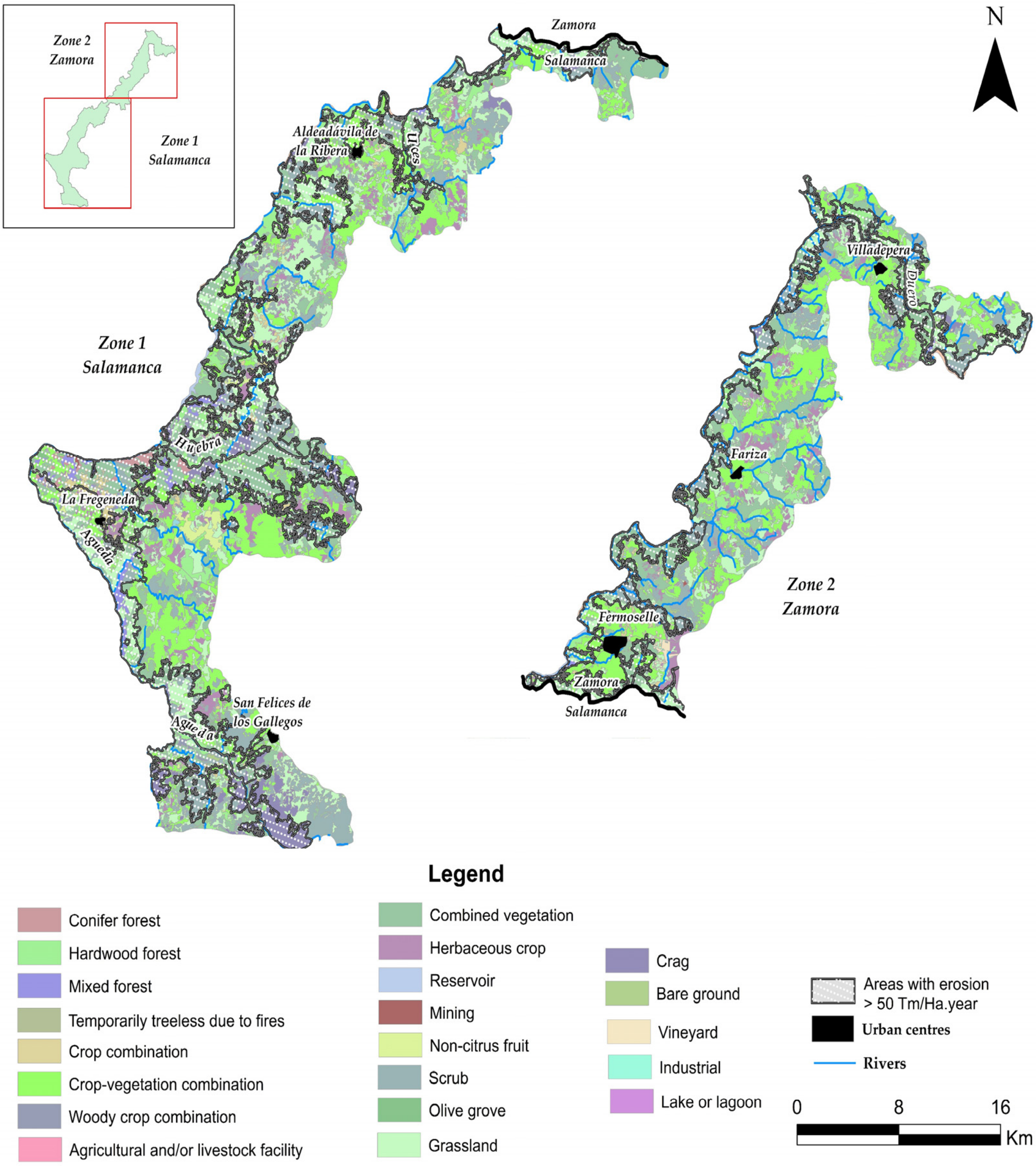

Figure 7. Land uses most affected by erosion. Zone 1: province of Salamanca; Zona 2: province of Zamora.

Figure 8. Conservation practices observed: (**A**) "Bancales"; (**B**) Terraces.

4. Conclusions

Currently, there are numerous methodologies for calculating the losses caused by water erosion in soils, most of them based on contrasted formulas but difficult to update and implement quickly taking into account current geomatic resources (high-resolution orthophotos, metric and centimetric lidar models, use of UAVs, etc.). Thus, as a novelty in this article, USLE has been implemented by means of factorial or parametric analysis in GIS, making it possible to generate an automated RUSLE model so that, with new and future technologies, erosion values can be improved in great detail. In this way, taking into account the determining components of the territory, two maps are obtained, one of potential erosion and the other of actual erosion, from which soil losses due to water erosion in the study area are calculated and quantified.

In the study area, three zones are differentiated according to their degree of erosion. The first ones are zones with an extreme level of erosion, losses of more than 200 Tm/ha/year, high slopes, poorly developed soils and vegetation with little protective power, low density and cover, such as conifers and broadleaf trees. The second ones are areas with moderate and medium erosion levels, with values between 10.1 and 50 Tm/ha/year, corresponding to the peneplain, with medium developed soils and vegetation with a certain degree of protection. The last ones are areas with tolerable levels of erosion (up to 10 Tm/ha/year) also coincide with penillanura but with more developed soils. The vegetation provides greater protection, as it has a higher density and herbaceous cover and makes this area less vulnerable to erosion.

In turn, these maps make it possible to establish in a simple way the degrees of erosion established according to the FAO, expressed in Tm/ha/year and mm/year and, together with the land use map, they constitute a low-cost non-structural measure that helps to identify the areas where it is necessary and urgent to implement conservation practices that mitigate soil losses. With this in mind, these measures will focus on reducing the length and steepness of the slope such as contour cultivation, "bancales" or terracing.

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Article

Characterisation of the Susceptibility to Slope Movements in the Arribes Del Duero Natural Park (Spain)

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Abstract: In recent decades, natural disasters have increased drastically, with slope movements being the most damaging geological hazard, causing thousands of deaths and considerable economic losses. To reduce these losses, it is necessary to carry out cartographies that spatially delimit these risks, preventing and mitigating the effects through the analysis of susceptibility in areas of great environmental value, as is the case of the Arribes del Duero Natural Park. For this purpose, different statistical methods combined with Geographic Information Systems have been developed. The susceptibility assessment methodology is carried out by integrating different thematic layers: lithology, geomorphology (slopes, curvature, aspect), hydrogeology and vegetation, performing map algebra and taking into consideration their weighting using deterministic methods (analytical hierarchy method). The susceptibility results are grouped into Very High, High, Medium, Low and Very Low so that the areas of Very High susceptibility correspond to areas of the high slope, without vegetation, south facing, with a lithology of quartzites, metapelites, and gneisses (canyons, steep valleys) and, in the case of very low susceptibility, with a lithology of quartzites, metapelites, and gneisses, On the contrary, the sectors of lower susceptibility coincide with flat areas, denser vegetation, north facing, with a lithology of conglomerates, pebbles, sands and clays, such as erosion surfaces or valley bottoms. The analysis carried out in this current investigation will allow the territorial delimitation of problem areas and the establishment of risk mitigation and management measures.

Keywords: slope movements; susceptibility; GIS; analytical hierarchies method process; Arribes del Duero

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1. Introduction

Natural disasters, in general terms, have increased dramatically in recent decades. Among the most damaging geological hazards are landslides or mass movements, which result in thousands of deaths and considerable economic losses [1,2]. The factors that play a role in enhancing these movements are conditioning factors and triggering factors [3]. The conditioning factors show the inherent characteristics of the terrain that make slopes susceptible to landslides, such as geology, geomorphology (slopes, curvature and aspect) and land use. Triggering factors, on the other hand, are extraordinary events such as prolonged rainfall, seismic effects or anthropogenic activities [4,5]. Landslides can be defined as mass movements of the ground, i.e., by gravity, and cause the collapse of steep slopes [6], which can be classified into landslides, avalanches and flows, both of rocks and soils [7].

Currently, landslides are one of the most common natural hazards which affect all regions of the world and cause great losses. Thus, in order to reduce them, there is a need to identify such events as a preventive way to mitigate risks by assessing their susceptibility, which can be quantitative or qualitative, based on the probability of occurrence under a set of geoenvironmental conditions [8–11].

In recent years, different methods have been developed for the elaboration of susceptibility maps that use Geographic Information System (GIS) techniques combined with statistical methods, such as multivariate analysis using regular discriminant grids, analysing the coefficients of each function based on the variables, making it possible to determine potentially unstable areas [12–17]. In addition, pairwise comparison methodologies are suitable for validating the results in different sectors [18], and in view of their usefulness and applicability, different specific software has been developed [19,20]. The use of landslide susceptibility maps has been used by different authors to predict landslides and their consequences, using bivariate statistical analysis or conditional analysis together with GIS tools, although it could be significantly improved by considering different types of landslides and using data with similar resolution in the case of bivariate analysis. As for the conditional analysis, being a simple method, it presents a certain operational complexity that does not allow the procedure to be carried out more times in the same area, having to use other techniques, such as the shell programme, which would entail more time and the possibility of errors [21–25].

One of the most widely used techniques consists of the integral interpretation of thematic base maps and their interrelation, with subsequent statistical treatment, by using direct or indirect, deterministic or non-deterministic methods [26,27]. However, nowadays, due to the wide availability of aerial images (aerial photos, satellite images) in a digital format, it is possible, by means of GIS, to integrate the different thematic layers and obtain a map of susceptibility to these movements. This method makes it possible to interact between thematic maps and to weigh each of the factors by establishing weights according to territorial characteristics, which can sometimes lead to a certain subjectivity [28,29]. To minimise this bias in the weighting process, statistical methods such as the Analytical Hierarchy Process (AHP) are used to provide a more detailed model for the elaboration of a landslide susceptibility map with objective empirical algorithms based on prior determination and sampling in laboratory analysis [30–38]. It is a very useful mathematical method for quantifying landslide triggers, as it allows for a simple and quick definition of the susceptibility map [38]. Likewise, susceptibility cartography is a very effective preventive measure because it is a basic tool for a correct assessment of the possible impact of natural processes on the territory. This cartography in itself constitutes a risk prevention measure, either by avoiding the location of human activities in areas of certain risk or by adopting protection measures for those elements exposed to risk when there is no other alternative. This way, it also serves to establish territorial zoning based on the possibility that landslides may occur and to establish areas prone to development [39,40].

The objectives of this article are to determine and map the sectors susceptible to landslide movements in the Arribes del Duero Natural Park based on existing land movements and their territorial characteristics and to identify the processes that cause them by providing useful information in the response phase in the event of a possible emergency.

2. Materials and Methods

The study area (Figure 1) in which this study will be carried out is the Arribes del Duero Natural Park, which is located in the west of Castilla y León, specifically in the northwest of the province of Salamanca and southwest of Zamora, along the Duero River and bordering Portugal. It is a protected natural area which comprises approximately 62,000 Ha and 38 municipalities. It stretches from the south of the park in Puerto Seguro (province of Salamanca) to the north part of the province of Zamora, where the towns of Fonfría, Pino and Villalcampo are located. From a bioclimatic point of view, it has a Mediterranean macroclimate, specifically a Mediterranean pluvial-stationary oceanic climate, with mild winters and very hot and long summers (average temperatures of 17.1 °C and rainfall of 500 mm) in the valley areas, compared to the climate of the plain area, (with temperatures of 12.2 °C and rainfall of 750 mm [41,42]. The landscape of the peneplain is undulating (with heights between 700 and 800 m); meanwhile, the steep slopes of the canyons and valleys (with heights of 130 m) of the Duero, Tormes, Uces, Huebra and Águeda rivers stand out in the valley areas. In terms of vegetation, the peneplain is a rich mosaic of species including *Quercus ilex*, *Quercus pyrenaica*, *Quercus suber* and *Quercus faginea*), other tree species, such as *Fraxinus angustifolia* and scrub species such as *Cytisus multiflorus* and *Cytisus oromediterraneus*), and also pastures and dry crops, such as wheat (*Triticum* sp.), barley (Hordeum vulgare), rye (*Secale cereale*) and vines (*Vitis vinifera*) can also be found. Olive trees (*Olea europaea*) and almond trees (*Prunus dulcis*) are still grown on terraces on the slopes. Finally, there are large dams and hydroelectric power stations, making it one of the areas with the greatest hydroelectric potential on the Iberian Peninsula [43,44].

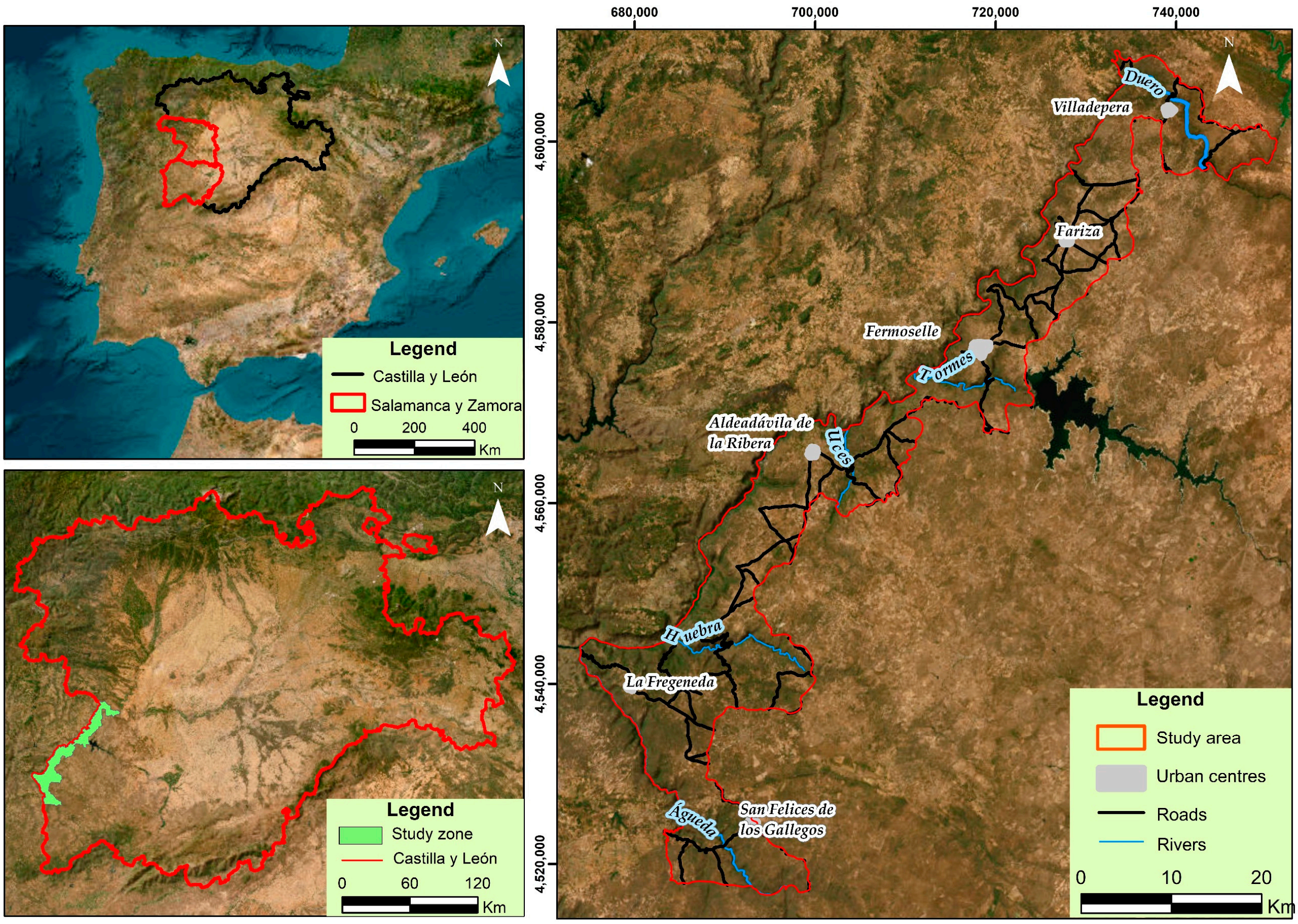

Figure 1. Location map of the study area.

The analysis of landslide susceptibility is carried out using non-deterministic methods, with thematic cartography in which conditioning factors for each type of landslide are identified. Susceptibility maps are obtained from this cartography of passive or conditioning factors [43]. Thus, the methodology followed in this article (Figure 2) combines fieldwork (the cartography must be validated via the direct observation of events in landslide areas and photo-interpretation of multi-temporal aerial photographs, with resolutions between 80 and 10 m) and desk-based work (each cartography has been made by using the Digital Terrain Model (DTM). All the above information has been obtained from the database of the Castilla y León Agrarian Technological Institute (ITACYL) [43–48]. Firstly, a compilation of information from historical events is carried out: cartographies from different organisations, analysis of aerial photographs from different periods, interpretation of orthophotographs and also direct observation in the field [43,44]. Then, the susceptibility or possibility of each area being affected by a given process is analysed. It shows the special probability of occurrence and results in the susceptibility map. This map takes into consideration the factors that control the occurrence of landslides. In this way, each conditioning factor is represented using thematic maps, and after using GIS techniques, they are also qualitatively reclassified using multivariate statistical methods into five classes according to behaviour in the face of potential landslide movements by assigning numerical values, thus simplifying the original map while retaining important information on landslide hazards. Five classes or degrees of susceptibility are established for ease of interpretation [49,50].

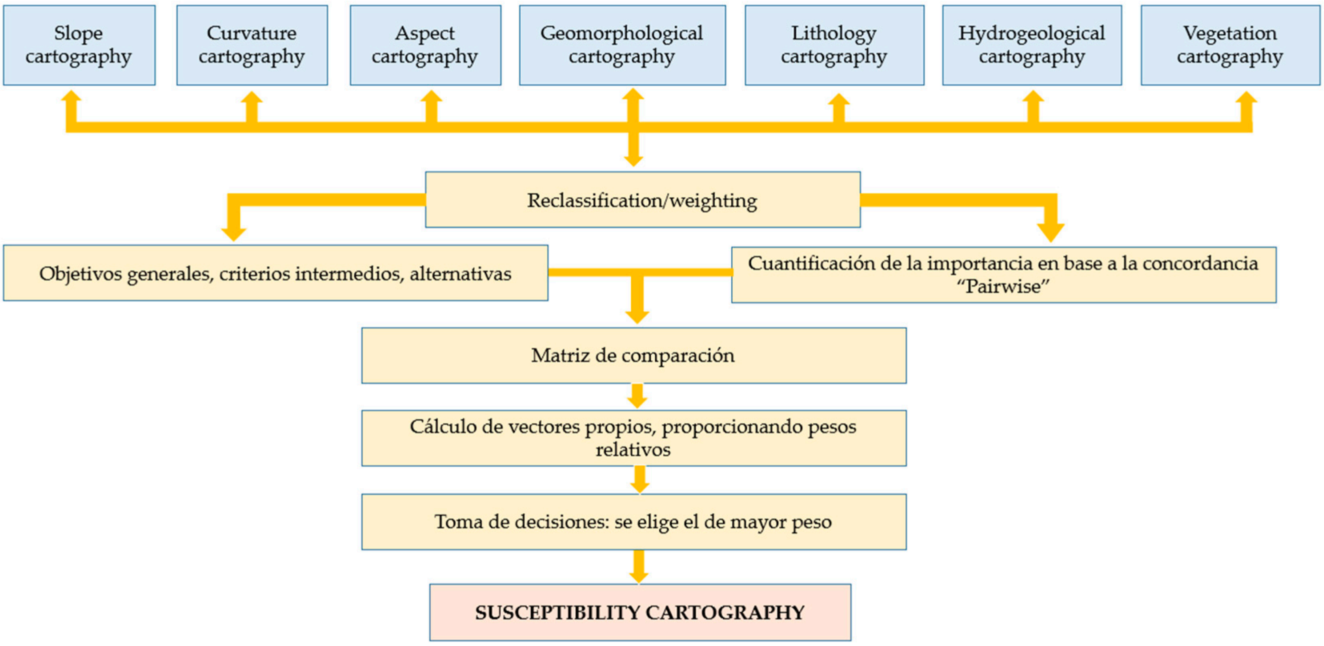

Figure 2. Methodological scheme.

The concordance matrix has been used as a statistical tool to find out the relationship of qualitative variables when combining the different categories. It shows the frequency with which particular combinations of categories occur for each of the variables. It allows comparisons to be made between pairs of items in a set to be recorded and organised, providing a useful structure for analysis and decision-making based on systematic comparisons.

Thematic factors are specific and different according to each zone [48]. In this study, seven thematic maps were evaluated. Each one corresponds to each factor analysed, and they are based on the Digital Terrain Model (DTM): lithological map, geomorphological domain map (slopes, curvature and aspect), hydrogeological map and vegetation map. Each of these maps is explained below:

- Geomorphological susceptibility: Geomorphological analysis is an essential step in landslide analysis [43]. This map has been drawn up on the basis of the geomorphological characteristics and distinguishes a series of units favourable to slope movements and the development of active processes.
- Susceptibility of slopes: The relief is a determining factor in the appearance of instability on a slope, being the angle of the slope the most important morphological parameter, as it will determine if slope movements exist and even the type of movements [43,51]. The slope map is made from a DTM digital elevation model, which provides a high-precision (1 m) map of the slopes using GIS tools.
- Susceptibility by curvature: The morphometry of the slope is one of the most important parameters in the possibility of slope movements. As a concave slope tends to accumulate more water after precipitation, it can retain it for a longer period of time, increasing the probability of occurrence of these movements. On the other hand, convex slopes correspond to rocky outcrops; thus, they decrease the probability of

these landslides [52]. The thematic map has been made by using DTM and taking into consideration the values of slopes and aspects. Cartography of slopes with a resolution of 1 metre has been obtained.

- Susceptibility by aspect: Aspect represents the direction of the slope face. It is necessary to take into consideration the influence of sills and shallows, which have a local effect as a conditioning factor in slope instability [52]. This map has been elaborated, as the previous one, by using the DTM.
- Lithological susceptibility: This is a parameter that will determine the potentiality of movements for each type of material. The analysis of the physical-mechanical properties (composition, deformability, degree of alteration, etc.) makes it possible to predict the stability or instability of a slope under certain triggering or active factors [45]. Thus, stronger rocks are more resistant to driving forces compared to weaker rocks and are, therefore, less prone to landslides [52]. For the creation of this map, the geological cartographies of the Spanish Geological Mining Institute (IGME) at a scale of 1:50,000 have been taken into consideration together with the DTM model. A more detailed lithological map has been obtained. Based on this map, the different lithologies were grouped into five degrees of susceptibility according to different parameters (Table 1).
- Hydrogeological susceptibility: It takes into consideration the structural and lithological characteristics, as well as their degree of alteration and permeability. This way, the loss of stability in the different materials is directly related to the position of the water table since water reduces the shear resistance because of interstitial pressures or increases the shear stresses because of soil saturation [44]. This map has been made taking into consideration the lithological cartography, as well as the permeability of the different materials.
- Vegetation susceptibility: Landslides are inversely associated with vegetation density [52]. Thus, the presence of vegetation controls the processes of weathering and erosion because it acts as a brake and plays a conditioning role in whether or not slope instability phenomena exist [50,53]. In order to draw up this map, different vegetation maps of the area, the distribution of vegetation in a semi-quantitative way, its presence or absence and type, and the reclassification used for the calculation of Factor C for water erosion risks, have been taken into consideration [54].

Table 1. Lithological strength assessment.

Type of Rock		Group/Origin /Composition	Properties (Average Values)					
			Coherence	**Cracking**	**Schistosity**	**Porosity**	**Solubility**	**Mechanical Behaviour**
Igneous Rocks		Volcanic Plutonic Philonian	High High High	Medium High High	Low	Low Very low Very low	Low Low Low	Variable High High
Metamorphic Rocks	High	Gneiss Micaschists	High Medium	High High	High Very High	Low Low	Low Low	High Low
	Medium	Schists Meta-quartzites Limestones	Low High High	High High High	Very High Low Low	Low High Medium-Low	Very low Low High	Very low High High
	Low	SlatesQuartzites	Low High	High Medium	Very High Low	Very low Medium	Very low Low	Low High
Rocks Sedimentary	Detritics	Sandstones Sand / Conglomerates ArkosesClay	Medium Low-M.L Medium Very low	Very low	Low	High Very high Medium Very low	Very low Very low Very low Very low	Low–Medium Very low Low–Medium Low
	Mixed	Marls	Low	Low		Low	Medium	Low

Once each of the cartographies has been produced, each of the thematic factors is reclassified and weighted into five different classes. In order to do this, the weighted superimposition technique is used, which allows a map to be developed by using superimpositions of several raster layers and giving weight to each of them according to their importance. Firstly, a concordance or "Pairwise" evaluation is established, which allows a relational analysis of each pair of parameters used in the assessment of risk susceptibility, by means of which the level of importance of each parameter is qualified and quantified by assigning a value between 1 and 4 (Table 2). It depends on the predominance of one parameter over another, and it is based on the movements inventoried in the study area. Then, by using the Analytical Hierarchies Method (AHM), the weights of each susceptibility parameter are determined (Table 3) according to the following steps (Figure 3): first, the general objectives, intermediate criteria and alternatives being considered in the decision are identified and organised in a hierarchical structure; second, a systematic comparison of pairs of elements within each hierarchical level is made by using a relative preference scale, which will tell whether one alternative or the other is more favourable; third, comparison matrices are constructed from the evaluations of the pairs of elements and each of which reflects the relative preferences of the elements at a specific level of the hierarchy; fourth, the eigenvectors of the comparison matrices are calculated, which will provide the relative weights for the elements at each hierarchical level; finally, decisions are made using the information obtained from the priorities. The best option selected is the one with the highest weight [55]. Once the weighting of each parameter has been assigned, the susceptibility map is obtained by the weighted overlay method using ArcGIS 10.8 software. All the cartographies, both thematic and susceptibility, are divided into two zones (according to the two provinces that make up the Park, Salamanca and Zamora) due to the fact that the study area is very large, losing details if they were presented in a single zone.

Table 2. Quantification of significance based on Pairwise matching.

Level of Importance	Definition	Description
1	Preference Similar	Criteria (x, j) contribute equally to the slope movement process.
2	Preference Moderate	Some slope movements are slightly favoured by Criterion (x) over Criterion (j).
3	Preference High	Criterion (x) dominates over criterion (j) in the slope movement process.
4	Preference Total	Criterion (x) contributes exclusively to the process of slope movement

Table 3. Determination of the weights of each susceptibility parameter by the Analytical Hierarchy Method.

Método MJA (j) (x)	Slopes	Curvature	Vegetation	Geomophology	Lithology	Aspect	Hydrogeology	Σ (x,j)/n	Relative Weight Σ (x,j)/n/Σ (x,j)
Slopes	1	4	3	4	3	2	2	2.71	0.26
Curvature	0.25	1	3	4	3	2	2	2.17	0.22
Vegetation	0.33	0.33	1	3	3	2	3	1.80	0.17
Geomophology	0.25	0.25	0.33	1	3	2	3	1.40	0.13
Lithology	0.33	0.33	0.33	0.33	1	2	3	1.04	0.10
Aspect	0.5	0.5	0.5	0.5	0.5	1	2	0.78	0.07
Hydrogeology	0.5	0.5	0.33	0.33	0.33	0.5	1	0.49	0.05
							Σ (x,j)	10.39	1

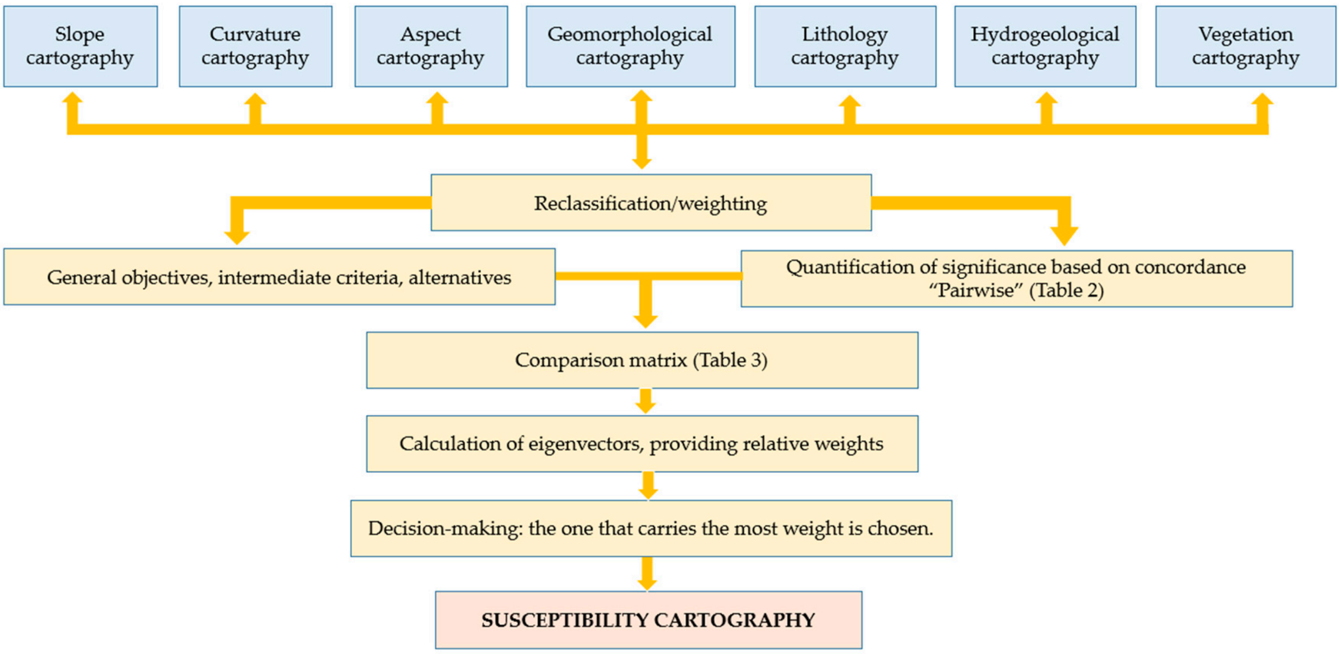

Figure 3. Weighting methodology.

3. Results

3.1. Thematic Cartographies

Each of the cartographies described below has been reclassified according to five susceptibility classes (Table 4): Very Low (value 1), Low (value 2), Medium (value 3), High (value 4) and Very High (value 5).

Table 4. Reclassification of thematic cartographies.

	Slopes	Curvature	Aspect	Geomorphology	Litology	Hydrogeology	Vegetation
Very high (Value 5)	>35°	Convex	South	Fluvial canyon, incised valleys quartz dykes, flat-topped granitic inselbergs and cone-shaped granitic inselbergs	Quartzites and Metapelites Gneisses	Quaternary unit	No vegetation
High (Value 4)	20°–35°	Rectilinear	West	Valleys, colluviums and dome-shaped granitic inselbergs	Shales and Schists	Granitic unit I	Herbaceus
Medium (Value 3)	15°–20°	Plane-Convex	-	Blockfields, Lomes	Leucogranites Biotitic Granites and Granodiorites	Granitic unit II	Sub-shrub
Low (Value 2)	5°–15°	Concave	East	Cones of dejection, aluvial fan and pediments	Porphyritic granites	Metasedimentary unit	Shrub
Very low (Value 1)	0°–5°	Plane	North	Floodpain, erosion surfaces, terraces, abandoned meanders, endorheic areas and granitic lehm	Conglomerates, pebbles, sands and clays	Quartzite unit and Gneisses	Arboreal postage

1. Cartography of slope susceptibility: In areas with steep slopes, landslides occur because the weathered material is not stable at that slope, causing some triggering factor (high rainfall) to activate the detachment of the overlying mass. On the other hand, in areas of medium and low slopes, there are areas of drainage concentration, which influences the greater or lesser infiltration, so the hydrostatic pressure causes the detachment of materials or rocks. Thus, the cartography obtained (Figure 4) shows

that susceptibility is very high (canyon areas, embedded valleys or quartz dykes) in the steeper areas, while in medium–high slope areas (20–35°), they are less steep or not as embedded as the previous ones (valleys, colluviums or domes). In turn, medium susceptibility areas are those of medium slopes (15–20°), such as crags or hills. Finally, the areas with lower slopes have low susceptibility (slopes between 5 and 15°), which are slightly inclined areas such as dejection cones, glaciers or ravines, and very low susceptibility, which are flat areas such as valley bottoms, navas, surfaces or terraces.

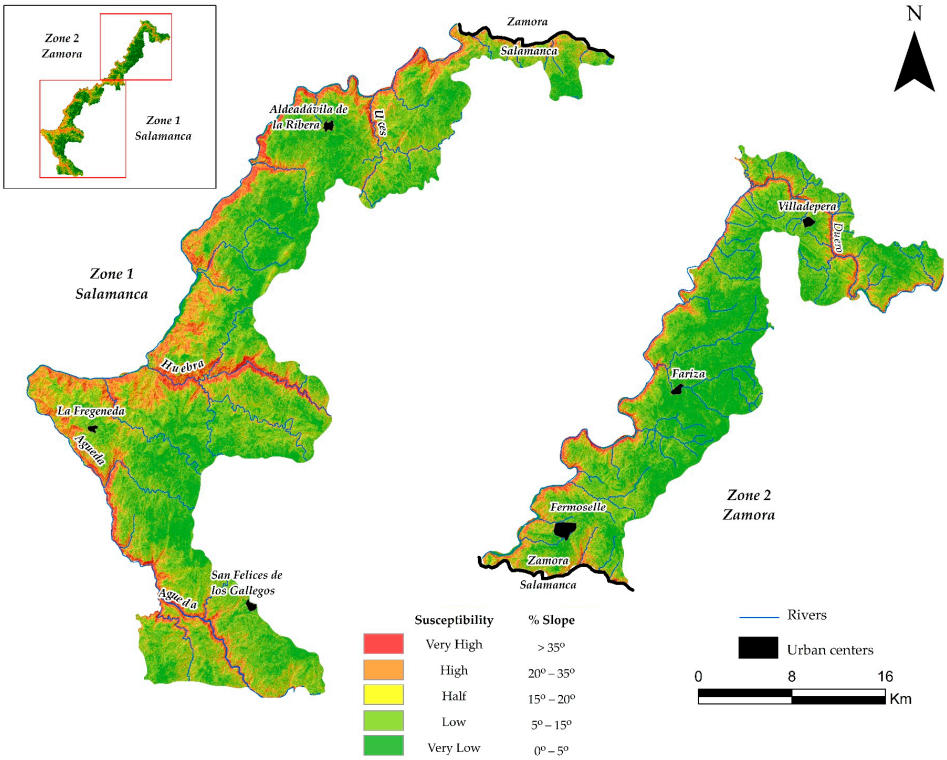

Figure 4. Slope susceptibility map.

2. Cartography of susceptibility by aspect: This map is based on the four aspects. Four susceptibility classes are obtained (Figure 5): Very high (South), High (West), Low (East) and Very low (North). The first two include sectors with an SW aspect that coincide with the Duero Canyon and the sloping valleys of the most abundant tributaries of the Duero. On the other hand, the Low and Very low susceptibility corresponds to areas where exposure is low because of the lack of topographic projections (surface or floodplain areas).
3. Cartography of susceptibility by curvature: It can be observed that the negative values correspond to convex morphologies, while concave and flat morphologies have positive values. Thus, convex shapes have a very high susceptibility, while flat areas have a low susceptibility. At the same time, this map allows us to differentiate between valley bottoms, erosion surface areas, terraces and ridges, among others. The degree of curvature, which is directly related to the ease of fall or retention of different materials, such as soil remediation, is also important.
4. Lithological susceptibility cartography: The calculation of this susceptibility has been based on the valuation estimated from the average value of the properties that determine the resistance of each lithology. Thus, in the map (Figure 6), the five classes are: Very high (quartzites, metapelites and gneisses), High (slates and schists), Medium (leucogranites, biotitic granites and gran-odiorites), Low (porphyritic granites) and Very low (conglomerates, sands and clays).

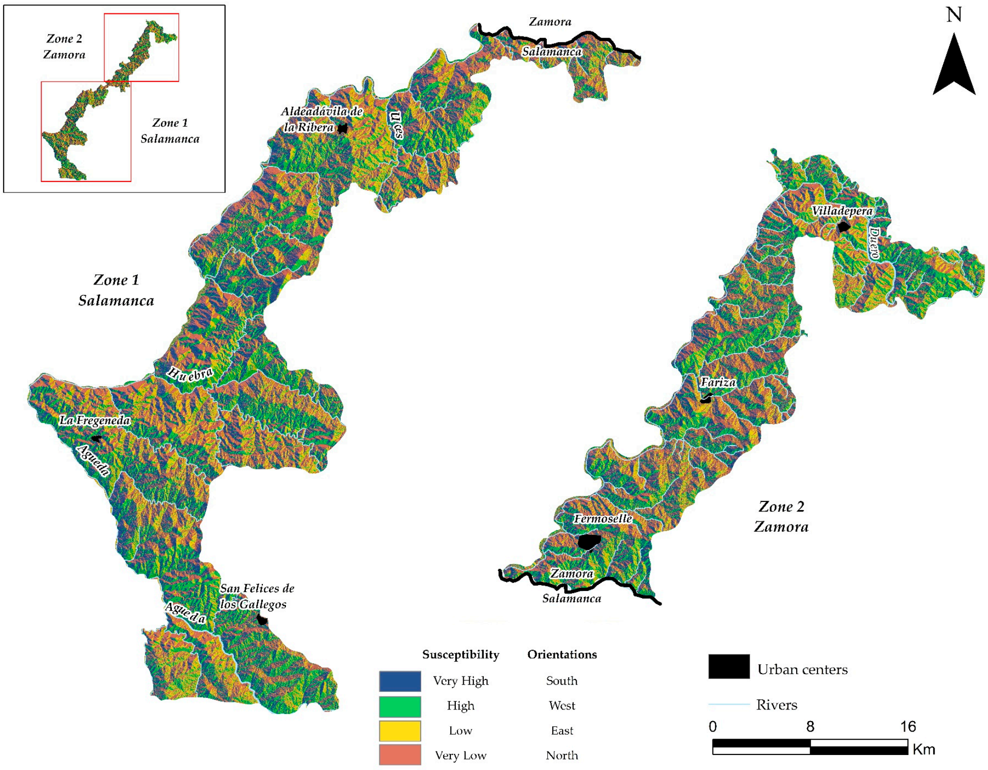

Figure 5. Map of susceptibility by orientation.

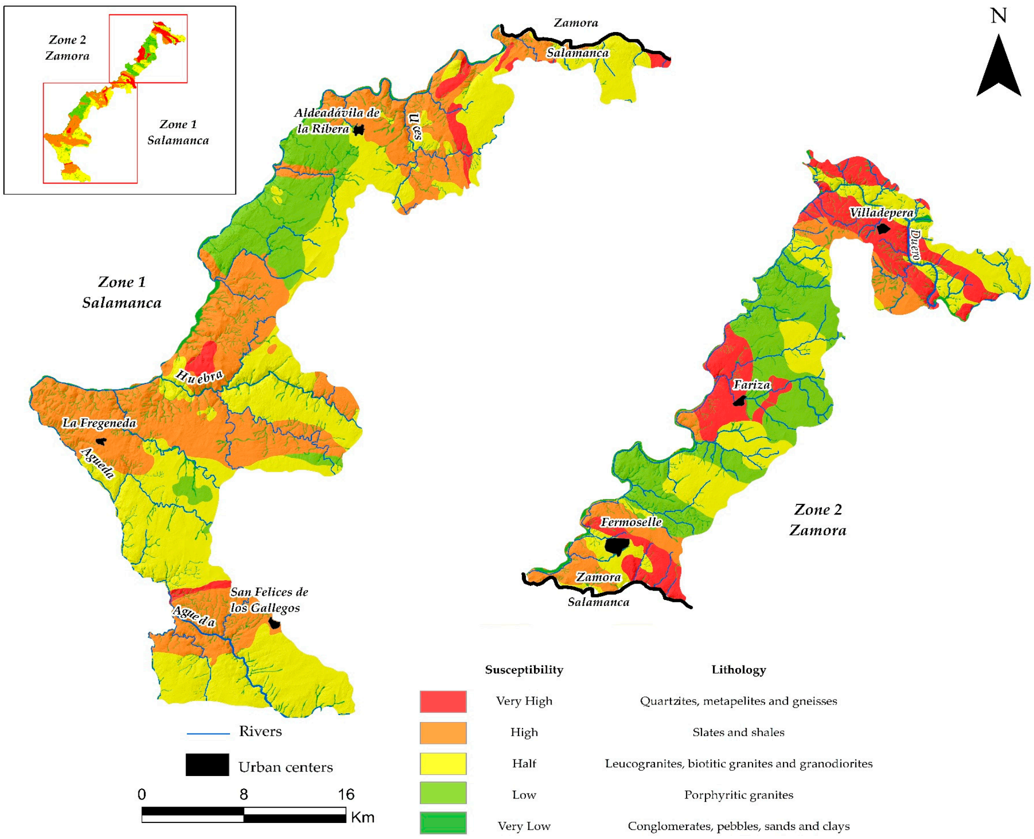

Figure 6. Lithological susceptibility map.

5. Geomorphological susceptibility cartography: It can be seen (Figure 7) that the areas of greatest susceptibility correspond to the steeper slopes, such as the canyon or the

boxed valleys (among others). On the other hand, the colluvium, valleys and domes have a high susceptibility; the berrocales, hills and granitic lehm have a medium susceptibility; the dejection cones, the "raña" (Plio-Pleistocene formation on a flat surface with semi-rounded ridges) and glacis have a low susceptibility and, finally, the flat or lower slope areas such as valley bottoms, terraces, navas and surfaces have low susceptibility.

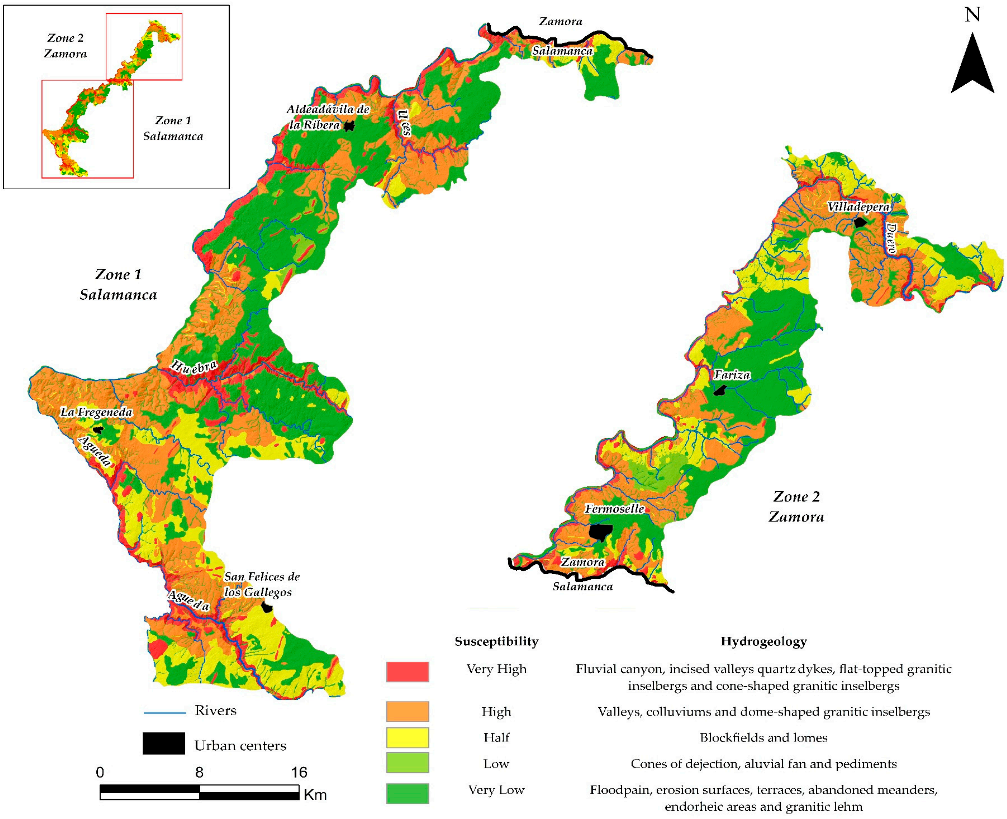

Figure 7. Geomorphological susceptibility map.

6. Hydrogeological susceptibility cartography: The following degrees of susceptibility are observed (Figure 8): Very high corresponds to the Quaternary unit formed by conglomerates, pebbles, sands and clays; High is the granitic unit I (formed by leucogranites and biotitic granites); Medium is formed by the granitic unit II (porphyritic granites); Low corresponds to the metasedimentary unit and, lastly, Very Low is formed by the quartzite unit and the gneisses.
7. Vegetation susceptibility cartography: In this map (Figure 9), we can observe that in areas without vegetation, as in the Duero Canyon, the susceptibility is very high and important external geodynamic processes that favour the instability of the materials that cover the slope are presented. In areas with the presence of herbaceous plants and crops (such as seasonal perennial grasslands or fallow land), the susceptibility is high, with a somewhat lower probability of these movements happening compared to the previous one. On the other hand, the sectors with subshrubby vegetation (cantuesares, tomillares and jarales or piornales and cambronales) and shrubby vegetation (fruit-bearing shrub formations and rocky areas with jaral-brezal) have medium and low susceptibility, respectively, since that they have a greater size than in the case of herbaceous vegetation. Finally, the areas with arboreal habitats (holm oak and cork oak groves, deciduous forests, holm oak meadows or oak meadows) have the lowest susceptibility because they have a more developed root system, favouring the stability of the slope by retaining and fixing the sediment.

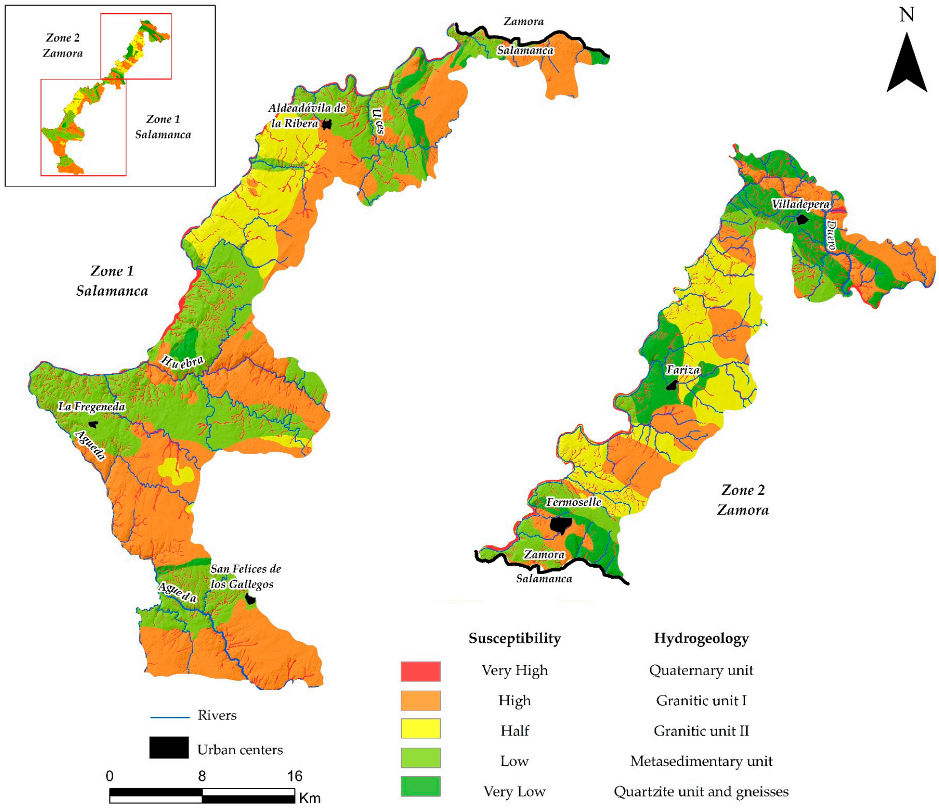

Figure 8. Hydrogeological susceptibility map.

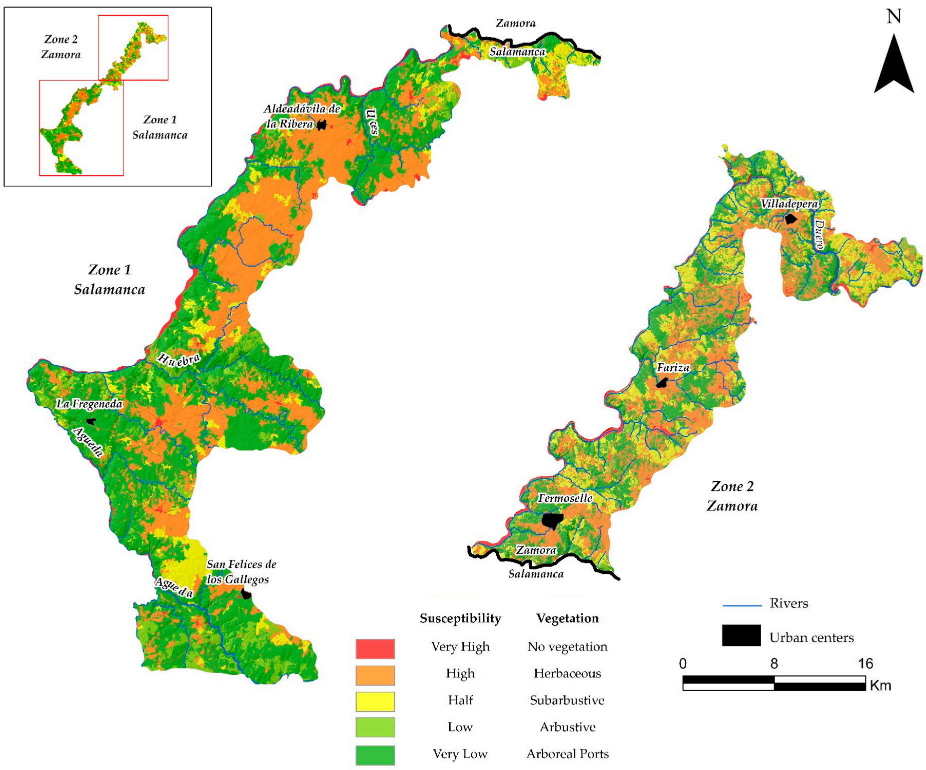

Figure 9. Vegetation susceptibility map.

3.2. Susceptibility Cartography

To obtain the susceptibility cartography (Figure 10), the weight of each parameter was established by taking into consideration the values given to each susceptibility unit: Very

Low (1), Low (2), Medium (3), High (4) and Very High (5). The established weighting has been applied to each parameter by using the Final Valuation (FV) equation (Equation (1)). To perform this by using map algebra, the parametric cartographies were multiplied by their corresponding weighting.

$$FV = (0.26 \times \text{slopes}) + (0.22 \times \text{curvature}) + (0.17 \times \text{vegetation}) + (0.13 \times \text{geomorphology}) + (0.10 \times \text{lithology}) + (0.07 \times \text{hydrogeology}) + (0.05 \times \text{aspect}) \quad (1)$$

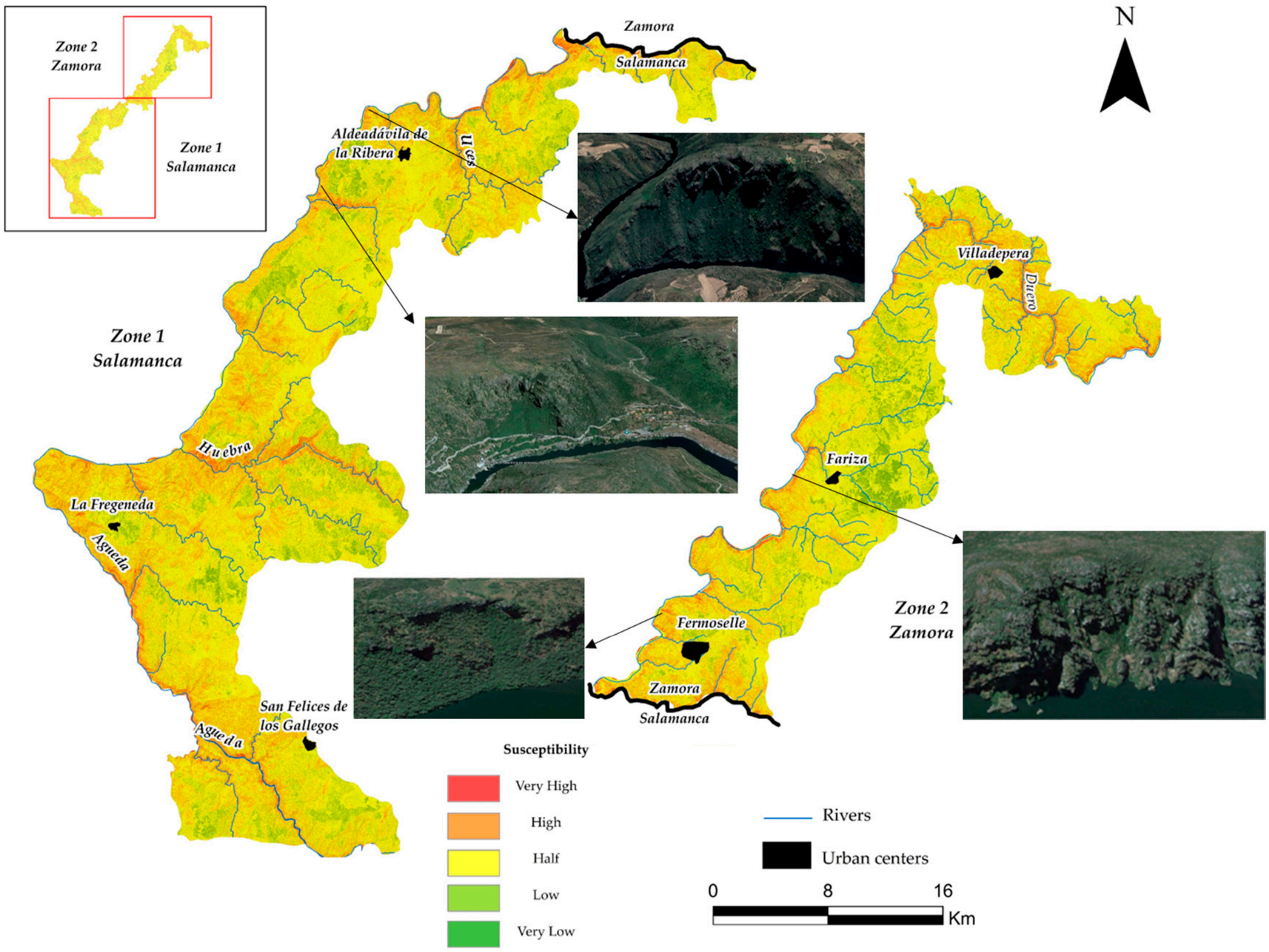

Figure 10. Susceptibility map.

According to the susceptibility cartography obtained, it can be seen that the areas with a very high possibility of slope movement occupy 5.1% of the area and correspond to the Duero River canyon and the valleys of the most abundant tributaries (Águeda, Huebra and Tormes), due to the high slopes and non-existent vegetation. In these areas, it is observed that colluvial landslides (Figure 11A), soil reptation (Figure 11C), granitic projections with associated landslides (Figure 11D,E), circular rupture scars with colluvial deposits down to the course of the Duero River (Figure 11F) and scars in the form of a circular curve of great amplitude with associated landslides (Figure 11G). On the other hand, the high susceptibility sectors, with an extension of 18.6%, correspond to the geomorphological domains of valleys, colluviums, escarpments (Figure 11B) and domatic forms, such as the one observed in the area between La Fregeneda and the river Huebra.

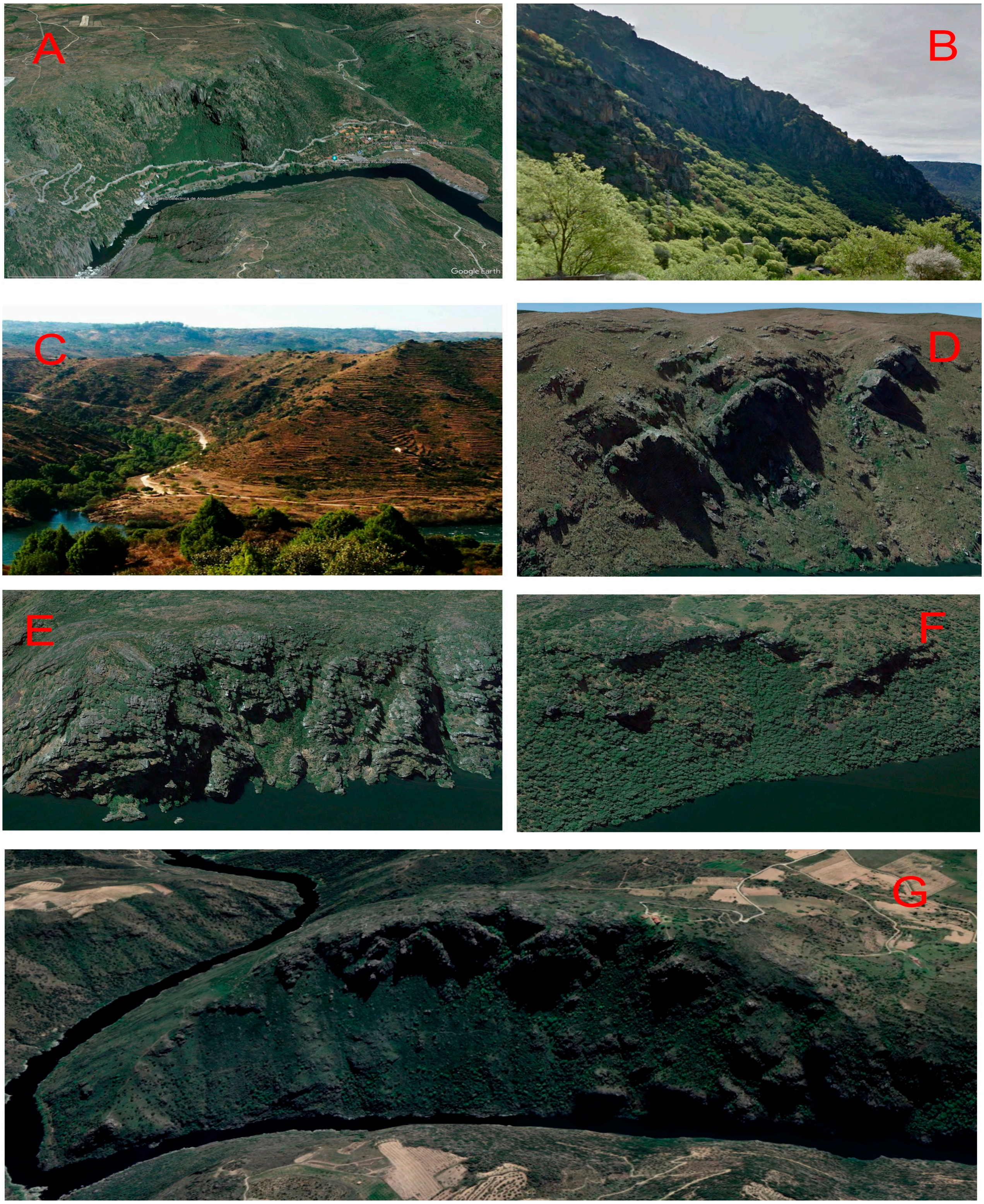

Figure 11. Colluvial landslide affecting the access to the Aldeadávila Hydroelectric Power Station (**A**). Detail of the escarpment and the colluvium at the foot, covered with vegetation (**B**). Mouth of the River Tormes into the River Duero at Ambasaguas-Villarino, where soil reptation and structural measures with terraces can be observed (**C**). Granite outcrops with associated landslides of the ledges or "viseras" in Fermoselle (**D**,**E**). Circular break scarp with colluvial deposits up to the course of the Duero River (**F**). Wide curca scar with associated landslides in Aldeadávila de la Rivera (**G**).

The medium susceptibility is the most extensive, with 65.7% of the surface area, corresponding to the crags and hills, berrocales and hills with a lithology of leucogranites, biotitic granites and granodiorites and vegetation of the subshrub type that already give them a greater fixation to the soil, unlike the previous ones, are found. As for the low susceptibility areas, they cover an area of 10.6% and are characterised by having slightly sloping surfaces, including glacis, raña and dejection cones, with shrub-type vegetation. They are located in very specific areas, such as in the Cerezal de Peñahorcada mountain ranges. Finally, the sectors of very low susceptibility are scarce and punctual, only occupying 0.04% of the area, corresponding with areas such as erosion surfaces, valley bottoms and terraces, with a high density of tree vegetation, which means that the rest of the parameters also have low values.

4. Discussion

Landslides are not instantaneous phenomena but occur gradually, conditioned by numerous thematic factors that act directly or indirectly. In Arribes del Duero, the most common factors used in various studies of this type have been selected [45–48]: geomorphology (slopes, curvature, aspect), lithology, and hydrogeology. To analyse and predict these landslides, susceptibility maps are used; however, the reliability of these maps must be considered, and both the limitations and advantages of their use must be considered [56].

Firstly, the quality of the cartography is important; a robust and reliable methodology that integrates different data sources and analysis techniques should be used. In this study, fieldwork, including direct observation of events and photo-interpretation of multi-temporal aerial photographs, was combined with desk-based mapping of conditioning factors. This integration, carried out using GIS, makes it possible to obtain a more complete and accurate susceptibility map [43,44].

However, the methodology followed has certain limitations, mainly depending on the quality and resolution of the DTMs; a high resolution entails a long calculation time, in addition to the need for more powerful workstations. All this must be considered when interpreting the results, as any error in these data can affect the final results of the susceptibility maps.

It is important to highlight that the choice of conditioning factors used also influences the reliability of the maps, and among these factors, the most important are slopes and vegetation. With regard to slopes, Arribes del Duero is characterised by two clearly differentiated areas, the canyon areas and sloping valleys, with high slopes, and the peneplain areas, with medium and low slopes. In the areas with steep slopes, landslides occur because the weathered material is not stable, causing some external factor to activate this gravitational movement, unlike what happens in the areas with medium and low slopes, where drainage is concentrated, influencing the greater or lesser infiltration. On the other hand, as regards vegetation, its presence increases the stability of the surfaces [57,58], the study area is characterised by a great diversity of vegetation, although there are also areas where there is none, such as the Duero Canyon, and it is there where susceptibility is higher, due to the existence of external geodynamic processes that favour the instability of the materials. In areas with vegetation, susceptibility varies depending on the density and tree size, so in areas with herbaceous plants and crops (low density and small size), susceptibility is high, whereas, in areas with tree size (holm oak and cork oak groves), susceptibility is lower because they have a more developed root system, favouring the stability of the slope.

Another important aspect to be considered is the selection of the weighting method of the conditioning factors, as it must be appropriate to these factors in order to obtain more accurate and reliable results. In this study, the evaluation of the concordance or "Pairwaise" has been used for subsequently analysis using the AHP method [56].

In terms of advantages, susceptibility maps provide useful information on the most landslide-prone areas. Additionally, if necessary, these maps can be validated and supplemented by detailed investigations. They also provide valuable information for areas where no previous events have been documented, helping to identify possible risks and take preventive measures. In addition, in emergency situations, these maps can be used in the response phase to identify more susceptible areas and make informed decisions.

In the specific case of the Arribes del Duero Natural Park, the susceptibility of gravitational movements, and indirectly, their associated risks, had not been previously analysed, unlike others, such as erosive risks [57] and natural hazards [59]. Thus, with the analysis of gravitational risks, it is possible to carry out, in the future, a study to analyse the natural risks of this park, to establish which areas are more susceptible to each risk and, with this, to establish measures to mitigate and manage the natural risks.

In summary, susceptibility cartography is a useful tool to determine the most susceptible areas; however, it is necessary to consider the limitations associated with the quality of the data, the selection of the conditioning factors and their weighting. Finally, it also provides additional information for those areas where no such events have been documented and useful information in the response phase to a possible emergency.

5. Conclusions

The susceptibility cartography, in addition to delimiting areas more prone to landslides, can be used in the future as a starting point to establish structural and non-structural measures for mitigation and management in territorial planning and human activities.

In the susceptibility cartography obtained, five susceptibility units are distinguished: Very high: these are areas with a very high possibility of landslide movement, with an extension of 5.1% and correspond to the Duero River canyon, the valleys of the most abundant tributaries (Águeda, Huebra and Tormes), such as: colluvial landslides, soil reptation, granitic projections, circular breakage escarpments, among others. Sectors of high susceptibility are the second most extensive, with 18.6%, corresponding to the geomorphological domains of valleys, colluvium, escarpments and domatic forms. Medium susceptibility, typical of the berrocales, with sub-shrub vegetation, is the most extensive, with 65.7%. Low susceptibility, is located in areas of slight inclination, such as glacis, rañas and dejection cones, and in addition to having more developed shrub-type vegetation, occupies an extension of 10.6%. Very low susceptibility corresponds to flat areas such as erosion surfaces, valley bottoms and terraces with higher density vegetation of arboreal type, being the least extensive, occupying barely 0.04% of the surface.

In view of the results, Very High susceptibility is present in specific areas, where it will be necessary to take some kind of measure to reduce the occurrence of landslides. Likewise, the susceptibility that most affects the study area is the medium susceptibility, which is not as important as the previous one, but where it is also necessary to establish structural and non-structural measures to mitigate these movements.

Finally, this cartography could be improved with the use of drones (UAVs) and orthophotos of maximum resolution, which would allow high-precision centimetric models to be made. This has the disadvantage of high data processing times and the need for a workstation capable of processing such data.

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Article

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].

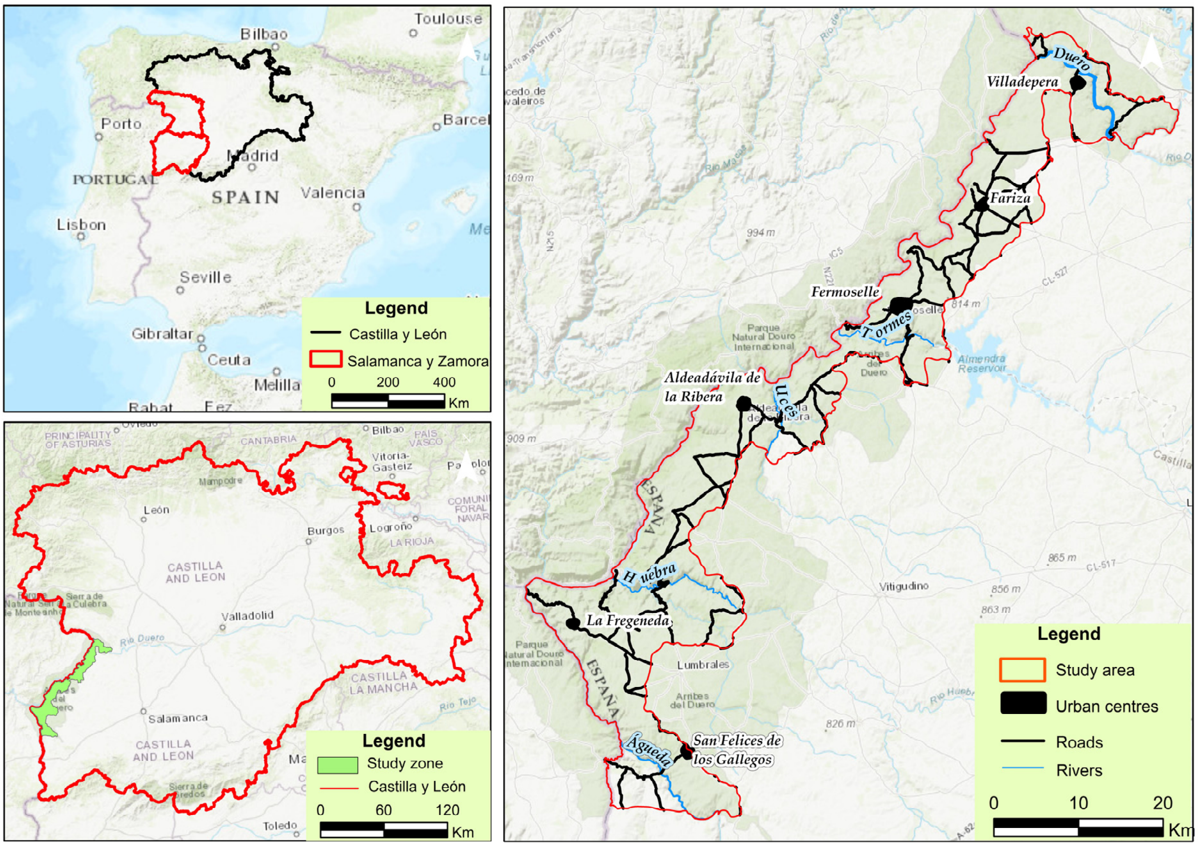

Figure 1. Study area.

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.

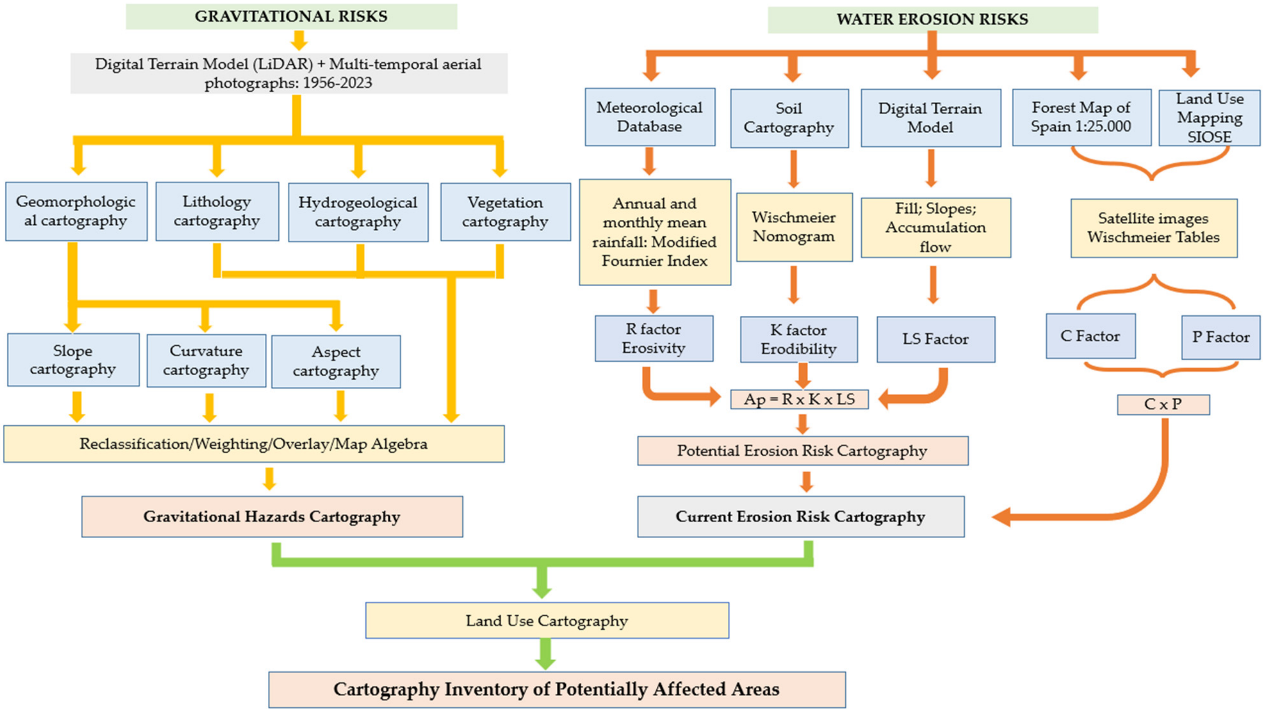

Figure 2. General methodological scheme.

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]:

$$IMF = \Sigma_{i=1}^{12} \frac{p_i^2}{Pt} \quad (1)$$

    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]:

$$R = 2.56 \times IMF^{1.065} \quad (2)$$

    - 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):

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

A: soil loss ($t * ha^{-1} * year^{-1}$); 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 non-structural 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.

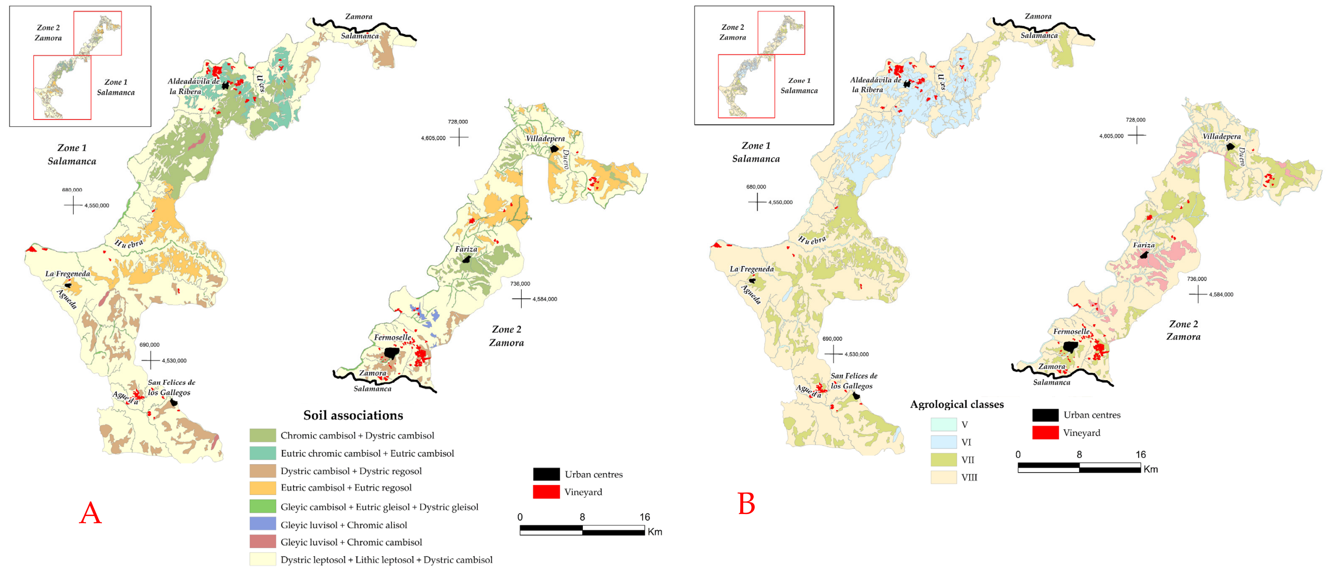

Figure 3. (**A**) Soils cartography; (**B**) Agricultural classes cartography.

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.

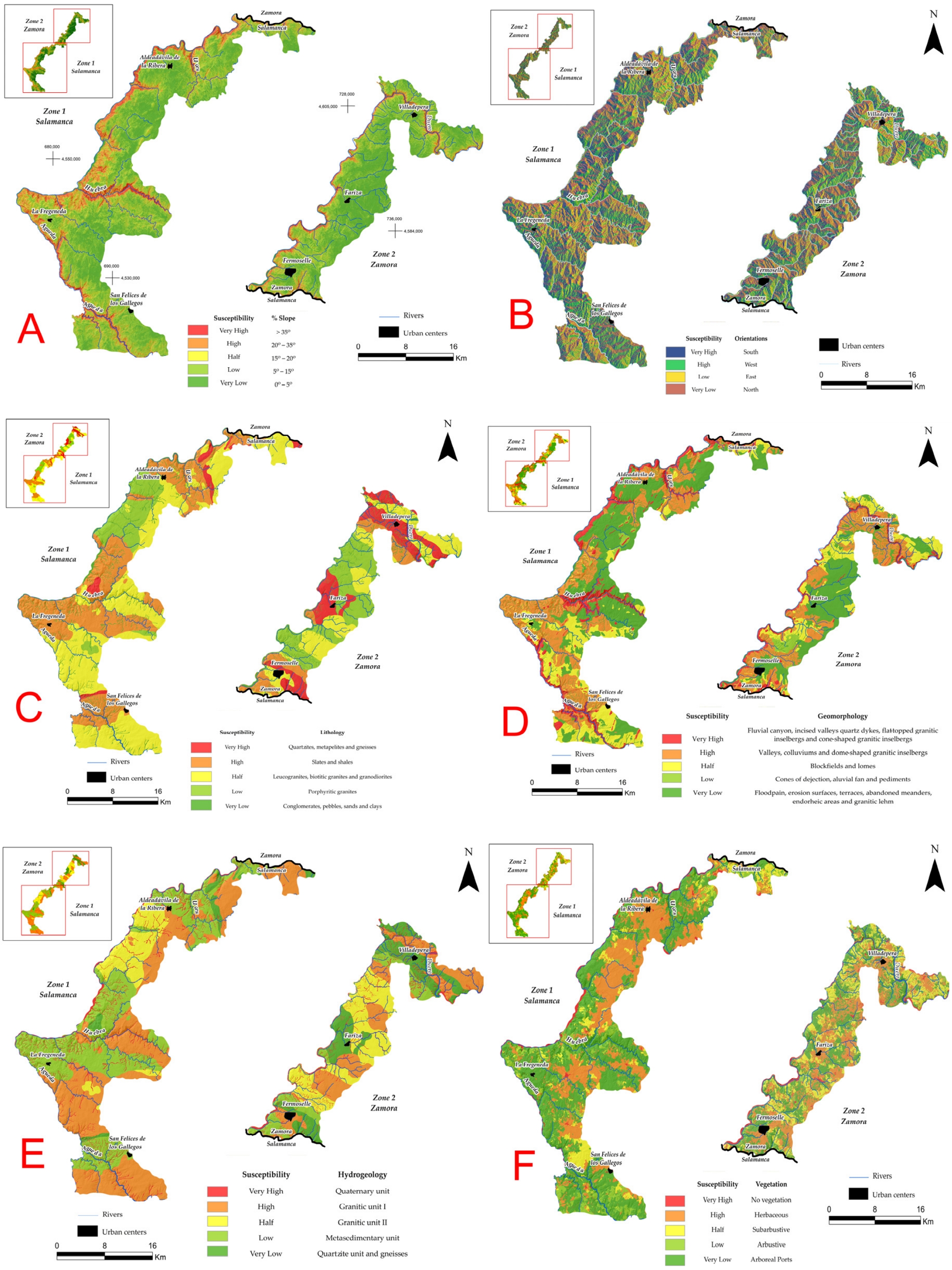

Figure 4. Thematic cartographies: (**A**). Gravitational slope risk; (**B**). Gravitational aspect risk; (**C**). Gravitational lithological risk; (**D**). Gravitational geomorphological risk; (**E**). Gravitational hydrogeological risk; (**F**). Gravitational vegetation risk.

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.

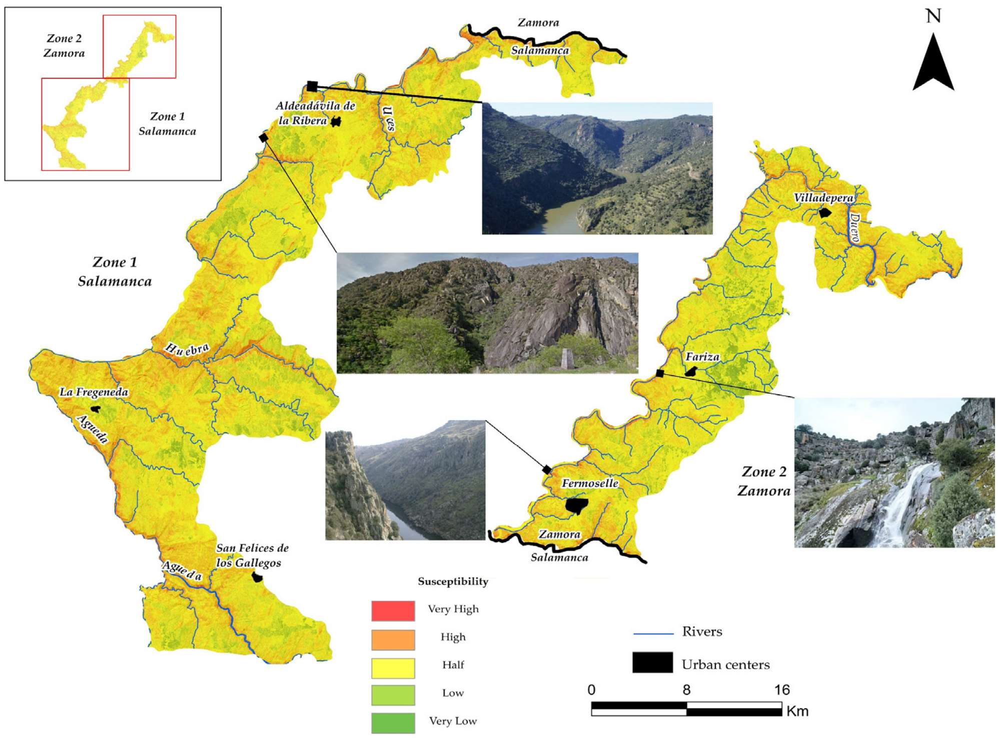

Figure 5. Gravitational erosion cartography.

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).

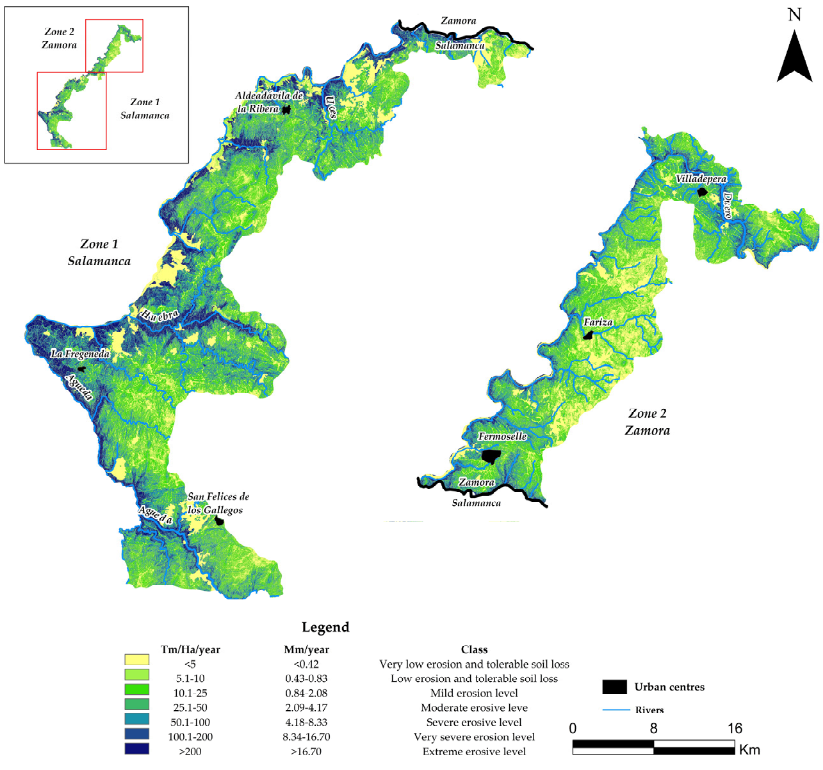

Figure 6. Current erosion cartography.

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).

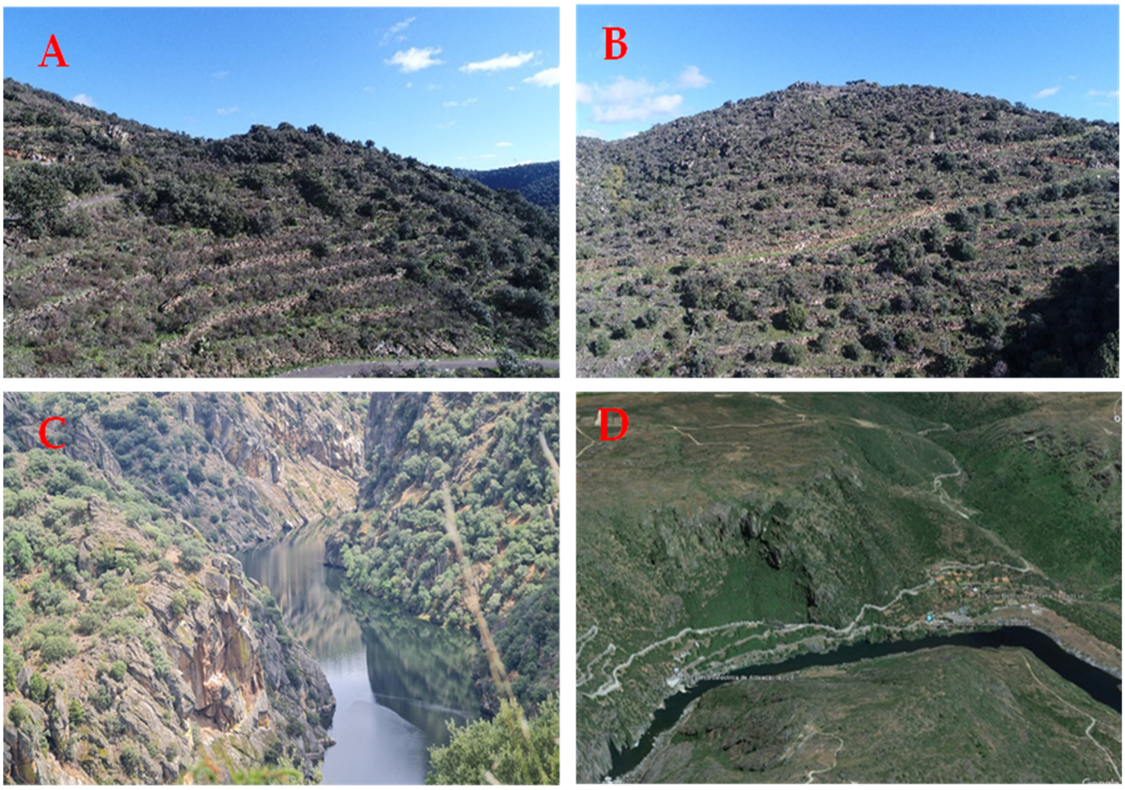

Figure 7. High susceptibility and high erosion areas with conservation practices: (**A**) "Bancales" and vineyards; (**B**) terrace and olive trees. Areas of high susceptibility and high erosion without conservation practices: (**C**) landslides; (**D**) colluvial landslides.

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.

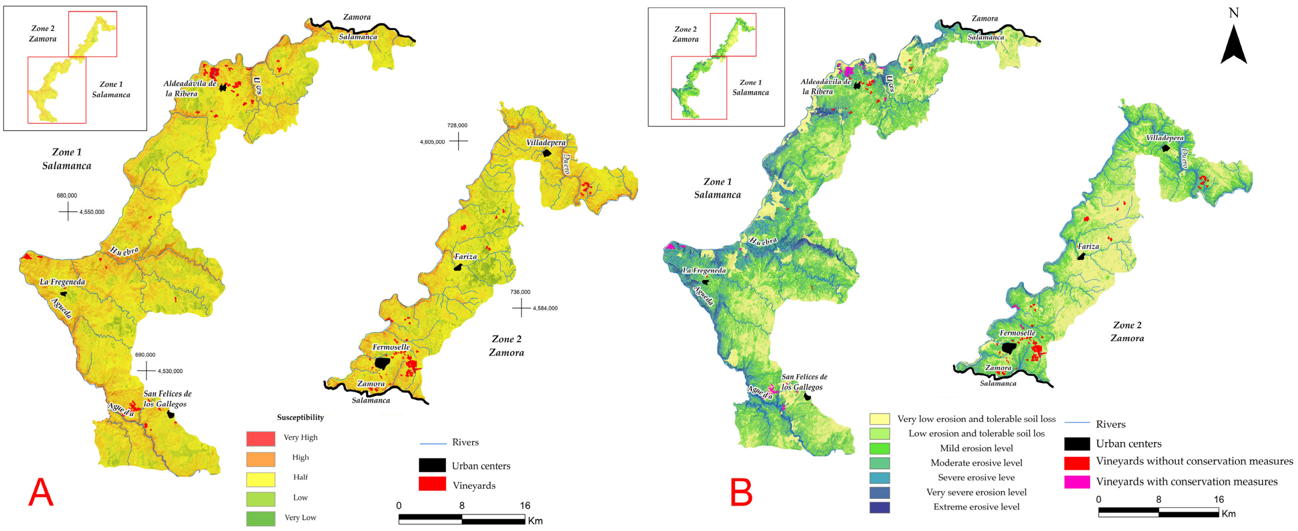

Figure 8. (**A**) Cartography of gravitational processes; (**B**) cartography of potential erosional sectors.

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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Article

Natural Hazard Characterisation in the Arribes del Duero Natural Park (Spain)

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Abstract: Natural disasters have been significantly affecting the natural and artificial environment for decades. For this reason, it is necessary to carry out adequate territorial planning in order to predict and mitigate possible natural risks in areas of great environmental value and interest, which is the case of the Arribes del Duero Natural Park. In order to achieve this, geotechnical mapping should be carried out followed by hazard mapping, taking into account the lithological, hydrogeological and geomorphological characteristics and, in addition, the real erosion rates. The results indicate that, in the study area, there are three areas with different geotechnical characteristics, classified according to their lithological, geomorphological and hydrological characteristics. In terms of hazards, there are five zones: with hydrological problems; lithological and geomorphological problems; geomorphological and hydrological problems; geomorphological and lithological problems; and geotechnical problems. Finally, it can be concluded that geotechnical mapping enables us to delimit areas of recommendations and limitations of use in terms of construction activities which, together with natural hazard mapping, will be very useful in the preparation of risk mapping for land-use planning.

Keywords: lithology; geomorphology; hydrogeology; geotechnics; natural hazards; Arribes del Duero

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1. Introduction

Natural disasters significantly affect the natural and man-made environment, which is why the management of natural disasters is currently a major challenge due to the different types of threats that exist [1,2]. Thus, the change of landforms due to natural disasters can affect and, in some cases, even restrict human interaction with the ecosystem [3–7]. Thus, to reduce the effects and socio-economic impact, adequate planning is necessary. For example, reliable information on special planning for natural disasters is a key tool for the selection of the most suitable sites for land-use development [8–17].

Geotechnical risk is a natural disaster that directly affects the ground, causing earth disturbances/movements, including earthquakes, subsidence, landslides or slope failure. These geotechnical hazards are not only triggered naturally, but some human activities can also increase their occurrence, increasing their severity. Therefore, as the natural risk cannot be avoided, human activities that may cause greater damage should be controlled. To this end, mitigation measures must be established, such as the creation of geotechnical and hazard mapping [18].

Studies of the characterization of natural hazards usually focus on the detailed examination of a single natural hazard. However, it is common for several natural phenomena to occur simultaneously or consecutively, therefore, a map would need to be created for each one, complicating their development [19]. In order to include all possible natural hazards, a simple analysis is carried out taking into account different characteristics (lithology, hydrogeology and geomorphology) and, based on these, natural hazard models are created, taking into account vulnerability and exposure to risk, through the use of geographic information systems [20–22].

On the other hand, the constant increase in different human activities and the commitment to protection and conservation means that sustainable development requires proper integrated territorial planning, which is a basic tool for predicting and mitigating natural risks in areas of great environmental value [23].

In order to carry out this territorial planning, some studies propose geotechnical mapping as a basic information prior to decision-making, which can prevent risk situations and can lead to significant socio-economic savings. This mapping is based on the sectoral characterization of the territory and its geomechanical behaviour in the short, medium and long term, establishing the possible natural and anthropogenic risks, as a consequence of environmental events or situations, induced by problems of geological characteristics (lithology, geomorphology and hydrogeology) [24].

In a complement to the previous mapping, and with knowledge of the geological characterization and behaviour of each material, there are also studies that carry out natural hazard mapping based on the sectoral analysis of the external geodynamic processes that can lead to a certain natural hazard [25,26]. This mapping predicts the existence of a certain risk or threshold based on a qualitative (geotechnical zoning) and quantitative (erosion rates) assessment, showing the importance of a detailed analysis of geomorphological, lithological, hydrological and geotechnical constraints in risk mapping for land-use planning [23].

The objectives of our article, in the Arribes del Duero Natural Park (Salamanca-Zamora), are: to carry out a geotechnical zoning of the territory, which allows a basic and preliminary geotechnical characterization, taking into account different factors (lithology, geomorphology and hydrogeology). On the basis of this mapping, potential natural hazards can be established by means of natural hazard mapping, in order to avoid these areas or to take the appropriate measures in the creation of different infrastructures (buildings, roads, etc.), and in addition, to avoid future natural hazards.

2. Geological and Geomorphological Context

The study area in which this study is carried out is the Arribes del Duero Natural Park (Figure 1). It is a protected area of 1061 km^2 located to the west of the provinces of Salamanca and Zamora, bordering Portugal. It has a population of around 17,000 inhabitants and is made up of 38 municipalities. In terms of climate, there are two different climates: in the valley areas, it is characterised by mild winters and very hot and long summers (average temperatures of 17.1 °C and rainfall of 500 mm), while in the plains there is an extreme continental climate, with temperatures of 12.2 °C and rainfall of 750 mm. The rainiest months are March, October, November and December, and the driest are July and August. As far as snowfall is concerned, it is scarce, with only a few days in winter [27]. The river network belongs entirely to the Duero basin, whose most important tributaries, all of them on the left bank, are the Tormes, Huebra and Águeda. The landscape is characterised, on the one hand, by an undulating peneplain (with a uniform height of 700–800 m) and, on the other, by the steep slopes formed by the canyons (with heights of 130 m) carved by the river system (Duero, Tormes, Uces, Huebra, Águeda). In terms of vegetation, the peneplain is a rich mosaic, with species of the Quercus genus (oak, melojo, cork oak and gall oak), mixed with other tree species (ash) and scrub (broom and broom), pastures and dry crops (wheat, barley, rye and vines). For their part, on the slopes, on terraces, olive and almond trees remain, only displaced by myrtle, holm oak and juniper groves, where agricultural use has been abandoned [28,29]. It should also be noted that this is one of the areas with the greatest hydroelectric potential in the Iberian Peninsula, with large dams and hydroelectric power stations.

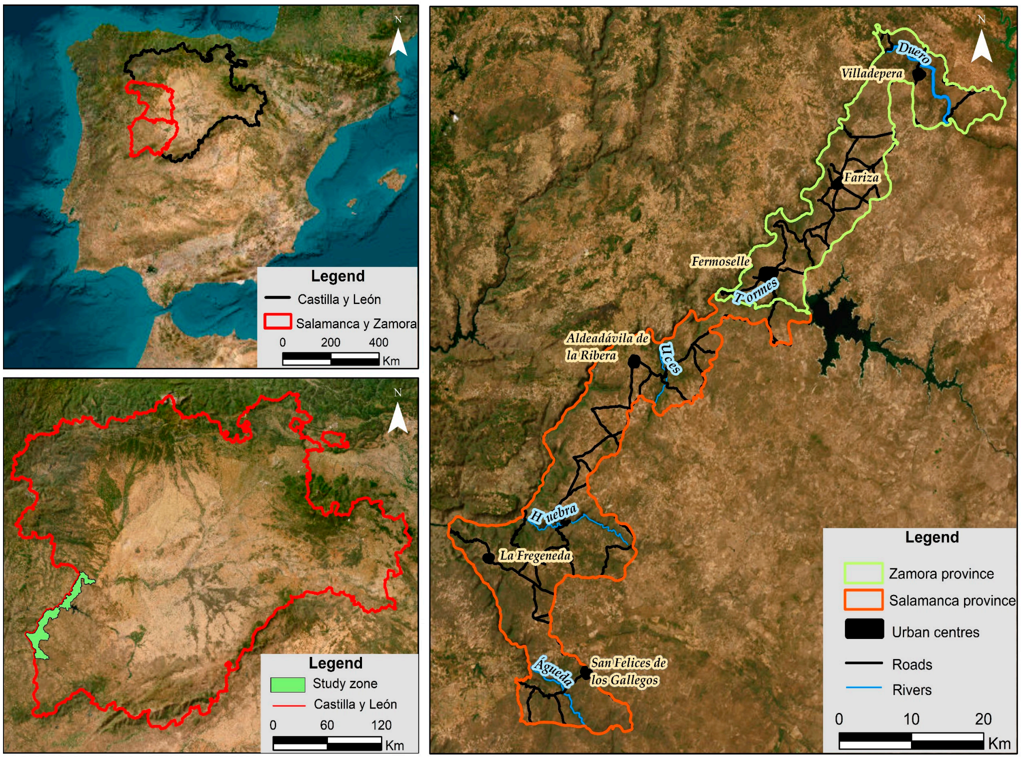


Figure 1. Study area. (**Top left**): Spain; (**bottom left**): Castilla y León; (**right**): study area divided into the provinces of Zamora and Salamanca.

2.1. Geological Context

The Natural Park is part of the Central Iberian Zone of the Iberian Massif, specifically on the west edge of the "Domo del Tormes". It is characterised by Precambrian and Paleozoic formations that were metamorphosed, deformed and intruded by plutonic granites during the Variscan orogeny. The materials affected by this orogeny are metasedimentary rocks belonging to the Upper Neoproterozoic or Lower Cambrian of the "Grauvaquian Schist Complex", discordant in turn under the Lower Ordovician Harmonic quartzites. In the lower levels of the metasedimentary series, there are abundant fine-grained glandular orthogneisses of Prevaric age, in addition to schists and slates. The metamorphism associated with this Orogeny transforms the sedimentary sequence (shales, schists and paragneisses) into metapelites and gneisses, reaching a partial merger with the generation and intrusion of anatectic granites (Figure 2). Tectonically, we can find concordant, discordant, mechanical or intrusive contacts, as well as faults and faults with indications of subsidence [30–35].

The acid rocks include a wide variety of leucogranites, biotitic granites. The former is porphyritic, two-mica, equigranular, fine-to coarse-grained, the latter may sometimes have tourmaline, garnet or cordierite and anatectic origin. Biotitic granites are always porphyritic and may (not always) have muscovite and/or cordierite. On the other hand, there are also intermediate and basic rocks that are related to the above, varying in composition from diorites and monzonites to tonalites and granodiorites [30,36,37].

As far as sedimentary rocks are concerned, there are slate, schist and paragneiss units, mainly clayey slate, chlorite and graphite schists, quartzite and conglomerate. The more frequent paragneiss, on the other hand, are biotite gneisses with marked schistosity and glandular [36,37].

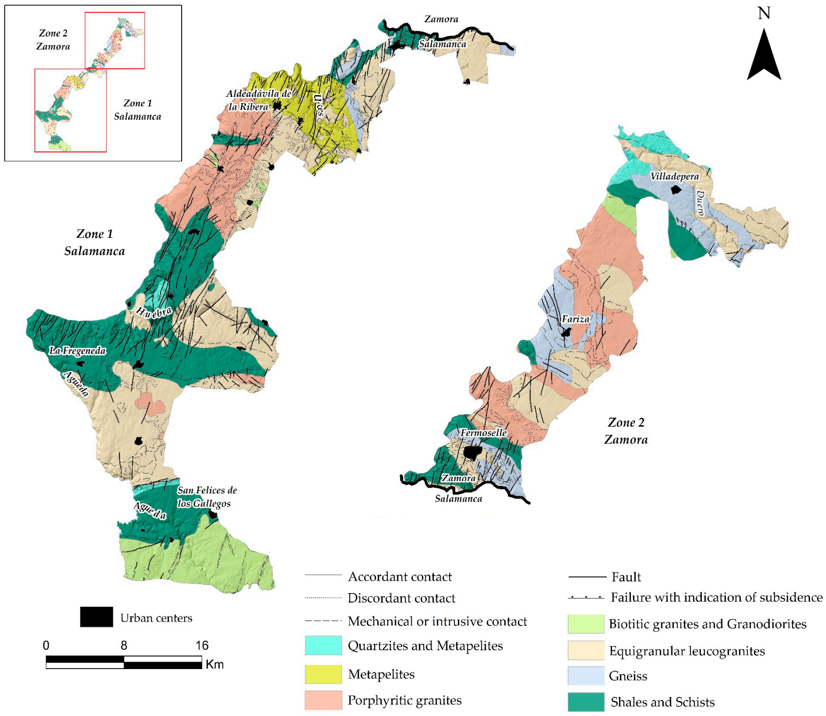


Figure 2. Geological map.

There is also representation of metamorphic rocks such as quartzites, belonging to the Ordovician, with white and yellowish tones, sometimes reddish due to iron oxide staining, which stand out against the surrounding terrain [30,35].

Likewise, in the fluvial network of river beds and riverbeds, deposits of materials such as conglomerates, pebbles, sands and silty clays are characteristic. The former is coarse to very coarse-grained detrital materials, poorly stratified and semi-dissolved, reddish or yellowish-brown in colour. The cobbles, on the other hand, are generally loose and are the product of the erosion of the Paleozoic mountainous reliefs, being of a quartz and quartzite nature and, to a lesser extent, cornubianites and slates [37].

Finally, the granitic and metamorphic basement is affected in its entirety by alpine faults, with a NE-SE or NNE-SSW direction, which condition the subsequent conditioning of the fluvial network. Some of these faults are associated with large quartz veins which form morphostructural alignments of mountain ranges in the peneplain, made up of milky quartz, sometimes marbled. Because of their resistance to erosion, they stand out clearly in the landscape, commonly known as "sierros" [37].

2.2. Morphostructural Context

In terms of geomorphology, most of the Arribes del Duero is located in the so-called "Zamorano-Salmantina peneplain", with a hilly to undulating shape, derived from the erosive processes of alteration, washing and fluvial erosion. It could be considered as a large surface area but, in reality, it is a multi-cyclic and staggered group, formed as a consequence of a relative lowering of the base level, rejuvenation of the network and reactivation of the landscape. In this way, six levels or erosional surfaces have been differentiated that are distributed gently staggered towards the west, a consequence of the tilting of the Meseta towards the Atlantic and, therefore, with ages later than the Oligocene [38].

In addition to these erosive surfaces, some residual reliefs in the form of island mountains, known as inselbergs, stand out topographically and in isolation from the monotonous profile of the peneplain. These have been formed due to the differential erosion, over long periods of time, of various morphogenetic processes typical of subtropical palaeoclimatic conditions. The inselbergs that can be distinguished in the area are flat-topped, conical and domical [38,39].

Other polygenic forms can also be observed, such as pediments and blockfields. The former are characterised by a gentle slope (no steeper than 5 degrees), which serves as a link between the river beds and the replans of steeper surfaces. Blockfields, on the other hand, are characterised by the concurrence of two or more types of cleavage, generally curved and subvertical, the former giving rise to lanchars and the latter generating parallelepiped blocks which, by granular disaggregation and flaking, produce granitic boulders [36].

With regard to the forms of slope, we can differentiate between escarpments, colluviums, slopes, valleys, incised valleys and the Duero river, known as the “arribe” or fluvial canyon. The first ones appear when there is a change of slope, the colluviums present a varied lithology depending on the materials that make up the substratum. The slopes are those areas where there is already a slight slope but without forming a valley. On the other hand, regarding the difference between valleys and incised valleys, in addition to presenting a clear V-shape, the former are attributed to less abundant streams or rivers and the latter to more abundant rivers, which give rise to more defined valleys but without reaching the boxing of the Duero [39].

The fluvial forms existing in the area are floodplain, which are areas of scarce development; terraces, which are deposits made up of silts and sands; cones of dejection, which are the product of the discharge of materials; abandoned meanders, which correspond to old valleys, abandoned by rivers or streams due to changes in the longitudinal profile; and, finally, aluvial fan (“rañas”), which are a mixture of colluvial and fluvial deposits of the floodplain, their lithology are sands and quartz and quartzite pebbles, of variable dimensions, generally loose, products of the erosion of the Paleozoic mountainous reliefs [39].

There are also endorheic forms, specifically navas. These are depressed areas of great extension and are associated with water retention phenomena, decantation, the development of hydromorphism and the generation of soils [39].

Finally, topographically, we can find different areas: flat, with slopes of 0 to 7%, i.e., erosion surfaces; intermediate areas, with slopes of 7 to 15%, corresponding to the slopes or glaciers; and steep areas with slopes of over 15%, such as the valleys of the Duero river (Figure 3) [37].

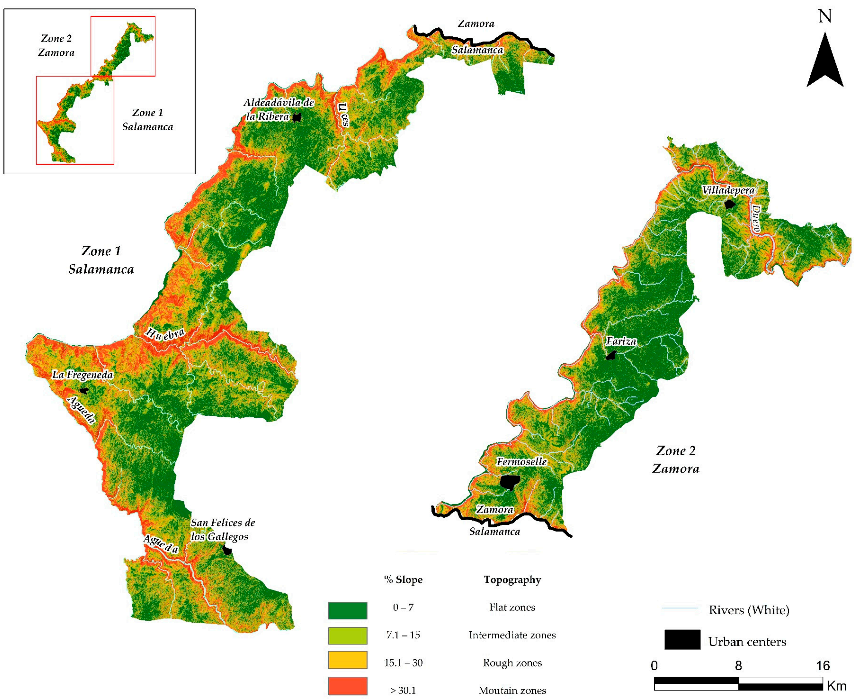


Figure 3. Slope map.

The hydrographic network belongs to the Duero hydrographic basin, the most important watercourses being, logically, the Duero, which borders Portugal at its north-western end, and its tributaries Tormes, Huebra and Águeda [37].

In terms of surface runoff, this can be considered good, except in localised areas. On the other hand, infiltration is very superficial due to the existence of impermeable rocks/soils substrates. The most permeable areas correspond to the floodplain [37].

3. Materials and Methods

The methodology followed in this article (Figure 4), combines field work with desk research, from which a series of cartographies are obtained that serve to establish the natural hazards and risks, in order to take measures to avoid them. The desk research focuses on the study of photographs, thematic maps and existing studies. All this information is contrasted with field work, by obtaining data such as lithological resistance using the Schmidt hammer or sclerometer, as well as observation and subsequent taking of photographs. In this way, to update and validate these data, tools from current methodologies have been used, such as the survey of four types of geomechanical station for each lithology [40–42].

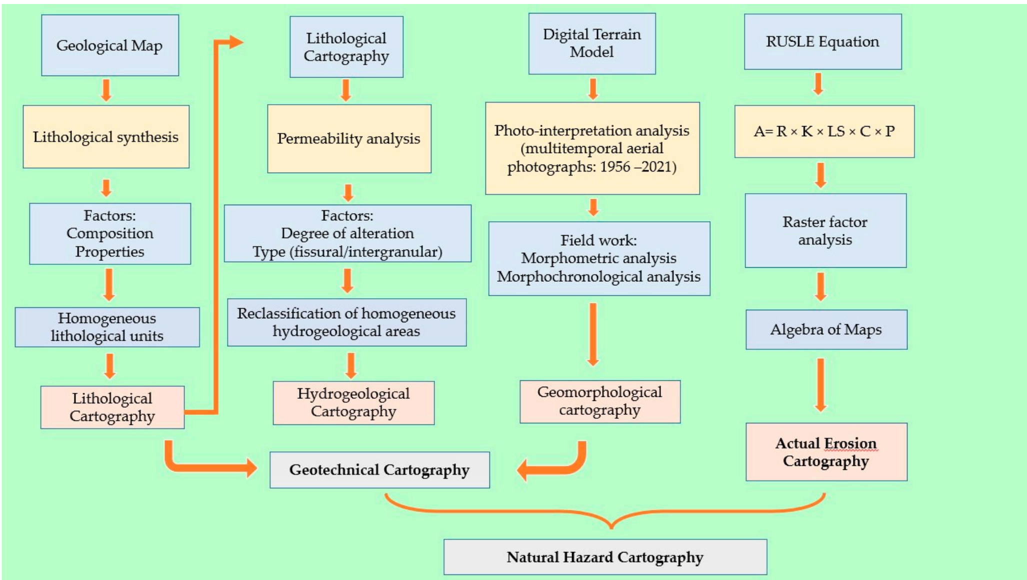


Figure 4. Methodological scheme.

In this way, considering the information previously indicated, the initial thematic cartographies (lithological, hydrogeological and geomorphological) are made, which in turn form the basis of the two final cartographies: "Geotechnical Cartography" and "Risk Cartography". The implementation of a Geographic Information System (ArcGis 10.8) has made it possible to work with georeferenced digital thematic layers.

The Geotechnical Cartography has been carried out by superimposing a series of thematic cartographies that will serve to establish territorial zoning categories, based on the grouping of homogeneous characteristics, where the response of the terrain can be similar according to its geotechnical behaviour [20,22]. They can be categorized as follows:

1. Lithological mapping: to make this map we have based ourselves on the grouping of areas that have similar characteristics in terms of composition and geomechanical behaviour. As for the characterization of the substratum, the existing geological maps have been used as a basis, grouping the materials according to composition and properties to create homogeneous areas. In the study area, there are three zones that have been classified, according to the age of the rocks that form them, as follows: Area I made up of plutonic outcrops (granites and gneisses); Area II corresponds to the Lower Paleozoic (metamorphic rocks); and Area III made up of Quaternary deposits (conglomerates, pebbles, sand and silty clays).

2. Hydrogeological mapping: this map has been made considering the characterization of the materials from the point of view of lithology and hydraulic parameters. For this purpose, the three previous areas have been reclassified according to the degree of alteration (high, medium and low) and type of permeability (by porosity, fracturing, dissolution and alteration).
3. Geomorphological mapping: the main morphological features that indicate their possible repercussions on the behaviour of the terrain have been taken into account, as well as the 1 m digital terrain model and the interpretation of aerial photographs and existing maps. Once this cartography has been carried out, a synthesised map is made with the fundamental aspects of the relief, in order to indicate only the most relevant physiographic characteristics, which can influence the geotechnical characterization and grouping of similar morphologies.
4. Actual Erosion Mapping: this is carried out on the basis of potential erosion mapping, which is obtained by multiplying three of the factors that make up the universal soil loss equation (RUSLE): R factor (erosivity), K factor (erodibility) and LS factor (slope). For the R factor, the average annual and monthly rainfall is taken into account, for the R factor, the granulometric characteristics of the soil and, for the LS factor, the length and steepness of the slope. Once this mapping has been obtained, the actual erosion mapping is carried out, taking into account the two remaining factors of the RUSLE: factor C (vegetation cover) and factor P (conservation practices). This mapping, together with the land uses, is useful to determine the conservation practices needed to mitigate erosion losses.

Natural Hazard Mapping, on the other hand, is based on the sectoral analysis of external geodynamic processes that can potentially lead to active processes. This mapping predicts, spatially, the existence of a certain hazard risk, based on geotechnical zoning and erosion rates [19,20]. In this way, it considers the Geotechnical Mapping carried out previously and the existing erosion map [37], which serves to add the risk of soil loss to the areas subject to other geomorphological, hydrological and geotechnical risks [19,20].

4. Results

In the study area, given its extension, we have installed four mechanical stations, the cards of two of them, specifically, one located on porphyritic granites and the other on slates and schists (Figure 5). Next, the resistance of the rock matrix is characterised by calculating the simple compression with the sclerometer or the Schmidt hammer (Figure 6A), as well as obtaining other useful data (Figure 6B,C).

Area I_1: from the lithological point of view, it corresponds to granitic outcrops (equigranular leucogranites, biotitic granites and granodiorites, porphyritic granites) with textures varying from fine-grained to porphyritic. It is frequent that the mass is crossed by dykes and veins of aplite pegmatites and quartz. In terms of geomorphological characteristics, the area is generally flat, with the exception of the western edge, in the vicinity of the Duero, which is steep. In addition, there are numerous outcrops, giving rise to the morphology typical of these, with extensive, hilly crags. Overall, taking into account the two previous characteristics, this area is considered to be stable. In terms of hydrogeological characteristics, it is considered to be impermeable material with a semi-permeable granular coating, with scarce internal drainage due to fracturing and diaclasation and acceptable external drainage due to active surface runoff. Thus, considering the above and after superimposing the different cartographies, we can conclude that the geotechnical characteristics of this area have a high load capacity and no foreseeable settlements.

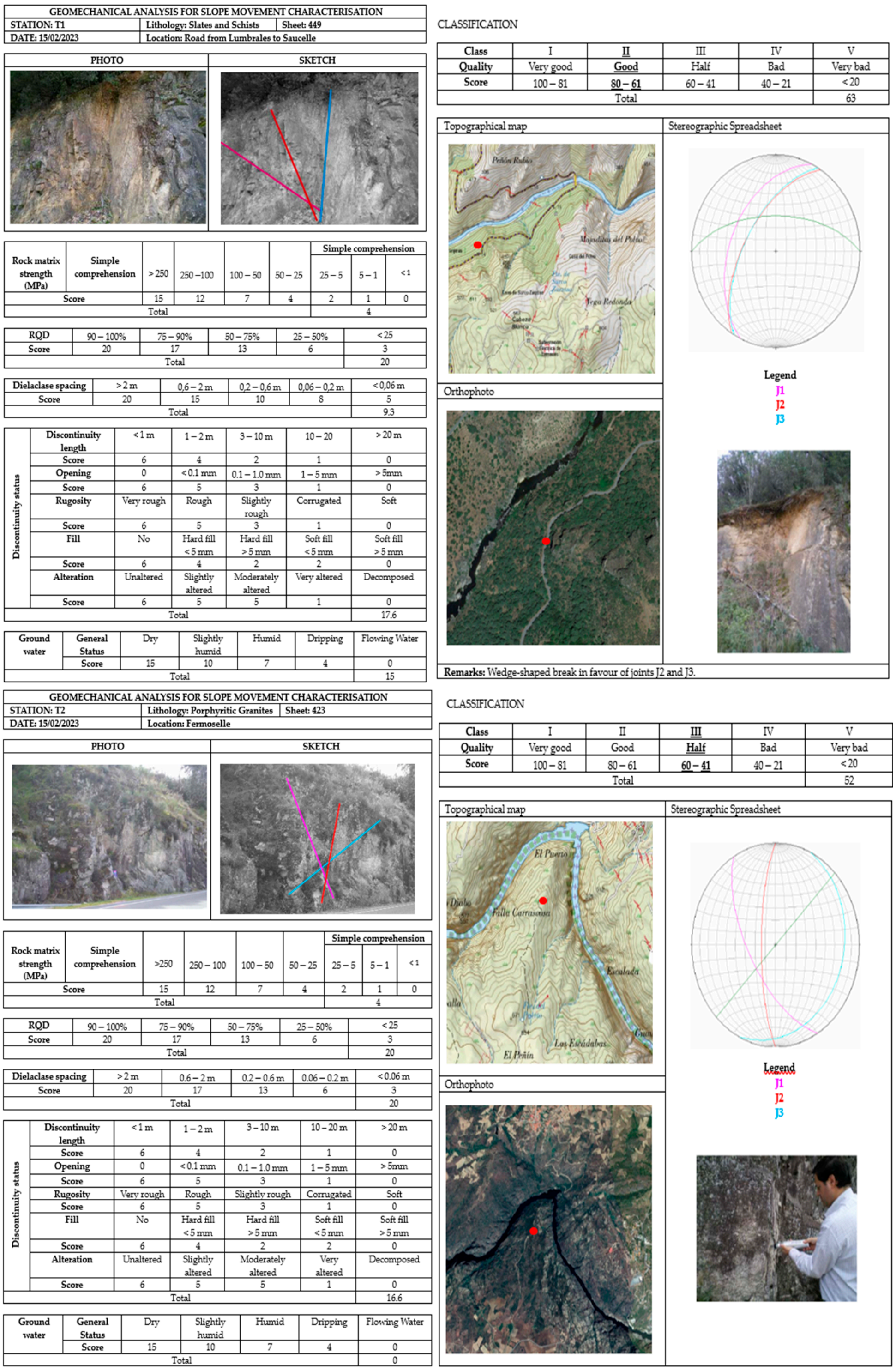
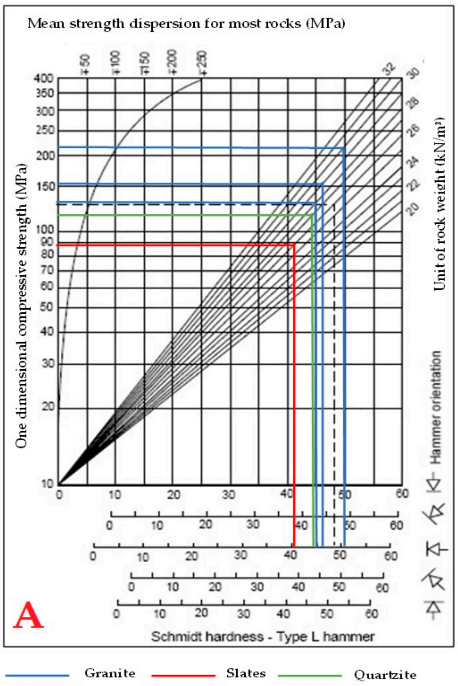


Figure 5. Geomechanical stations sheets.



Profile	% sand	% silt	% clay	Textural classes	Geological material
P1	38.27	50.81	10.92	Loam	Slates
P2	33.85	57.98	8.17	Silt loam	Slates
P3	72.55	22.16	5.29	Sandy loam	Slates
P4	46.77	45.84	7.39	Loam	Slates
P5	72.45	22.34	5.21	Sandy loam	Granites
P6	57.74	32.20	10.06	Sandy loam	Granites
P7	59.23	25.13	15.64	Sandy loam	Granites
P8	82.44	7.54	10.02	Loamy sand	Granites

B

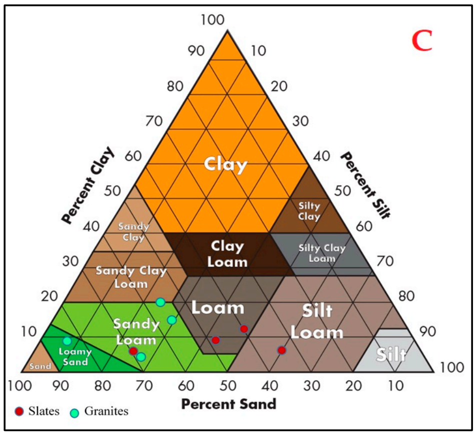


Figure 6. (**A**): Application of Schmidt's hammer; (**B**): particle-size distribution of soil samples; (**C**): soil texture classes (USDA).

4.1. Geotechnical Cartography

The Geotechnical Cartography has been made from the superposition of the lithological (Figure 7), hydrogeological (Figure 8) and geomorphological (Figure 9) cartographies, differentiating three areas that have been grouped according to homogeneous characteristics. The areas are described below (Figure 10):

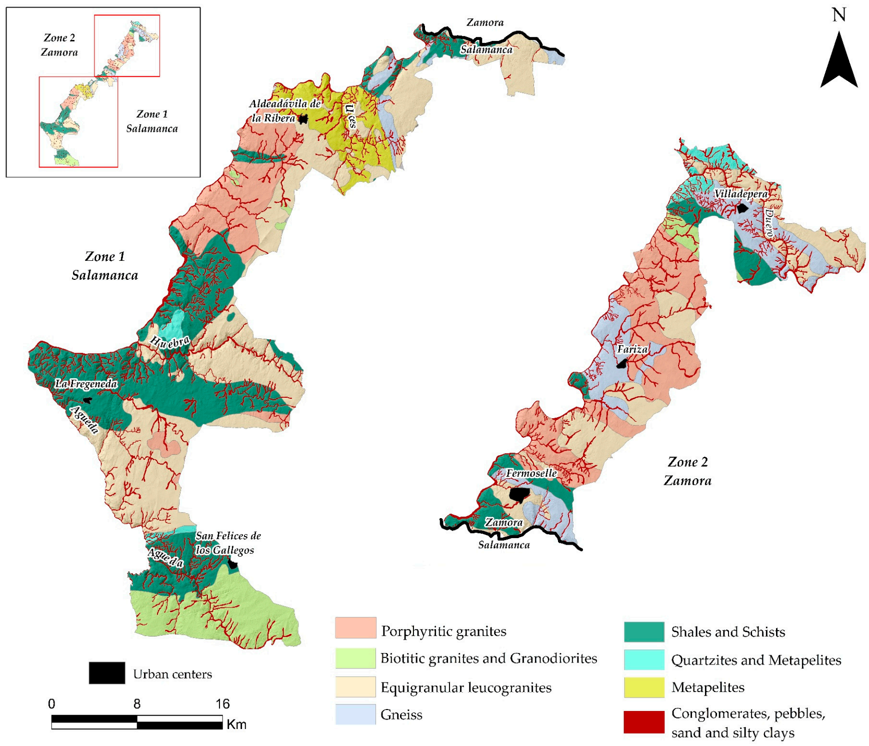


Figure 7. Lithological cartography.

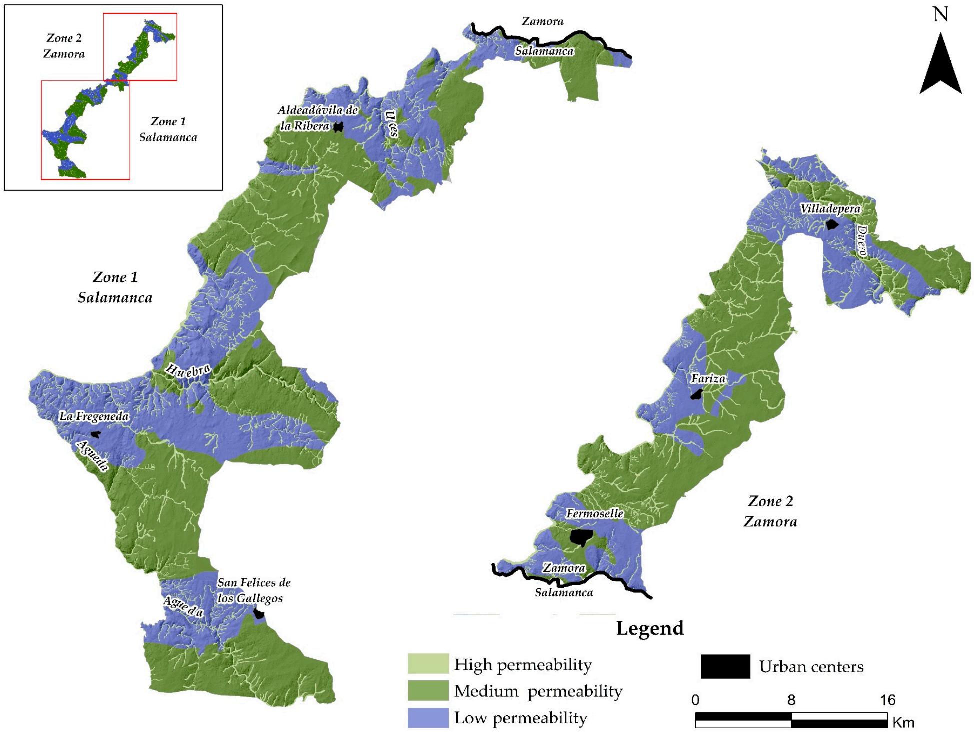


Figure 8. Cartografía hidrogeológica.

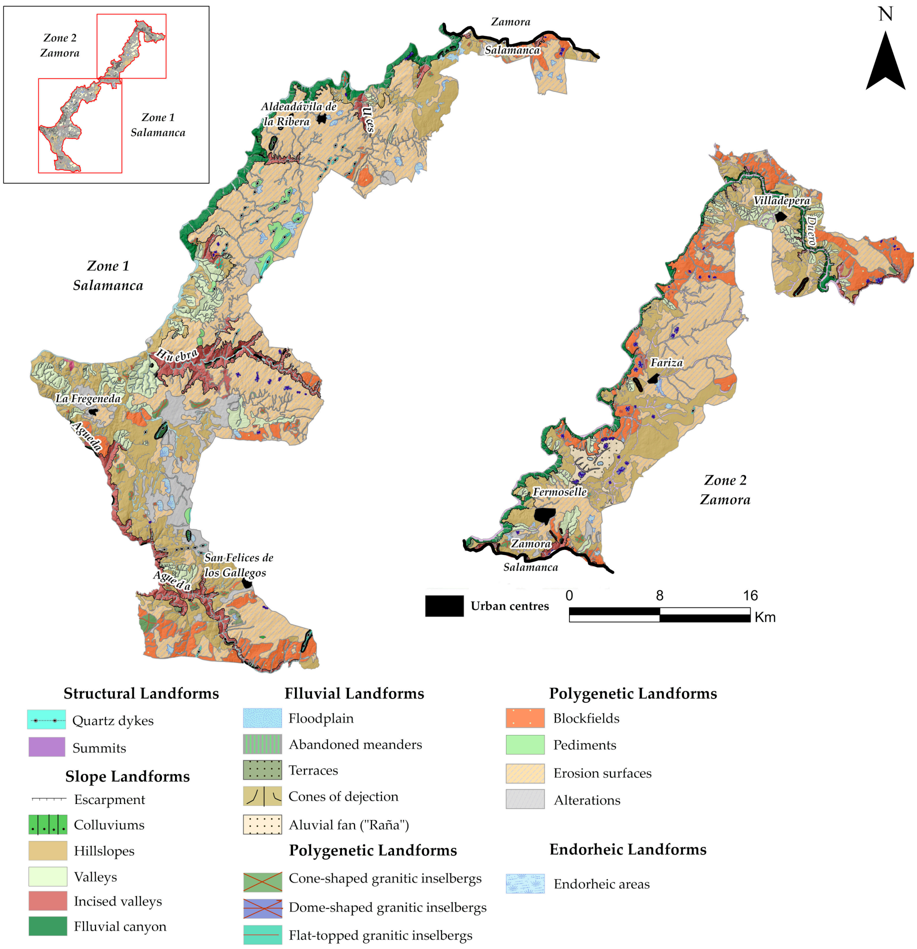


Figure 9. Geomorphological cartography.

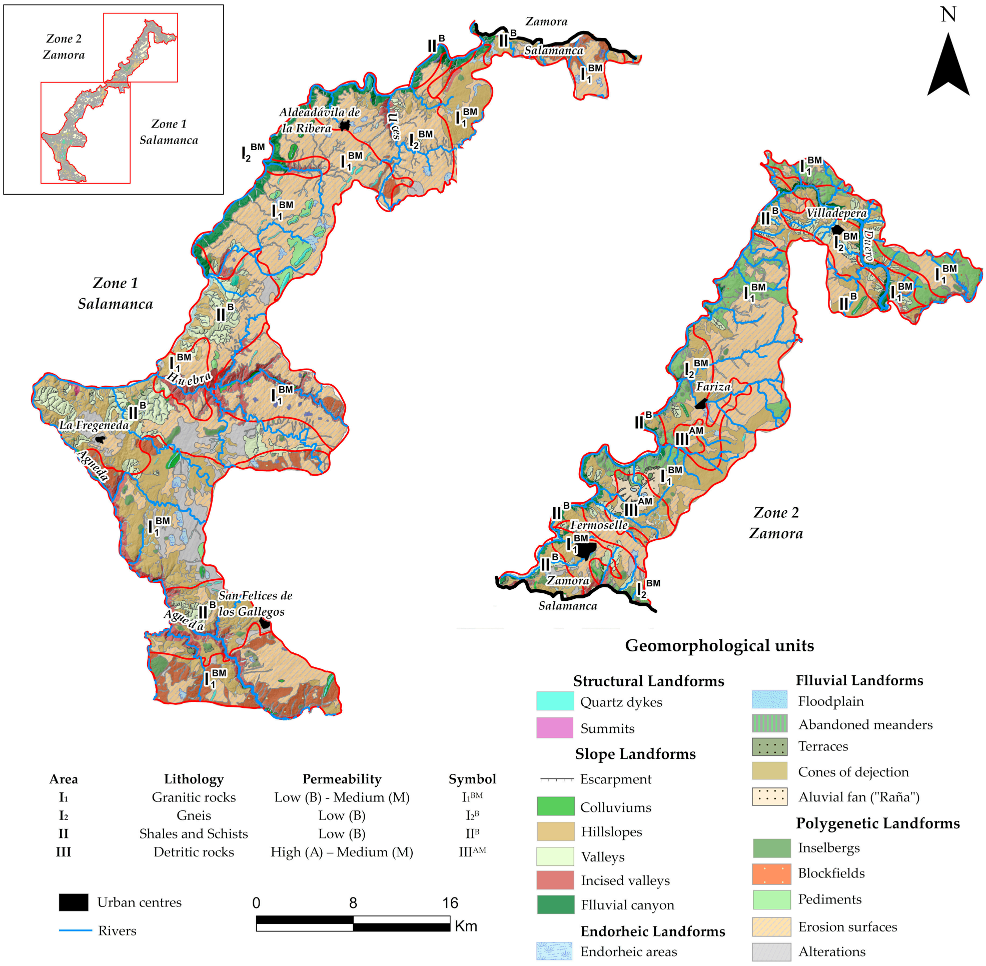


Figure 10. Geotechnical synthetic cartography (lithology + hydrogeology + geomorphology).

Area I_2: in contrast to the previous one, the outcrops in this area are scattered and consist of glandular gneisses and micacites. In terms of geomorphological characteristics, it has a flat topography, with slopes of less than 7%, except in the Duero river junction, which gives rise to a sharp drop in slope. Thus, taking into account the lithological and geomorphological characteristics, this area is considered to be stable. The hydrogeological characteristics indicate that they are impermeable on a large scale, although with a certain degree of internal drainage due to fractures and diaclases, with the presence of a more or less accentuated porosity. As far as drainage is concerned, it is good by active surface runoff. Thus, taking into account the above, the geotechnical characteristics of this area, similar to I_1, present a high load-bearing capacity in areas of sound rock. However, if the foundations are laid on fractured areas, the bearing capacity can be significantly reduced, and therefore the settlement cannot be of high altitude.

Area II: the lithology corresponds to Palaeozoic metasediments, made up of slate, schist, greywacke, quartzite and limestone. It has a flat topography, with the exception of the Duero river, where it becomes abrupt. The slate materials make this area unstable, without ruling out strong instability phenomena such as landslides. As for the hydrogeological characteristics, these are impermeable materials, with clay-loam textured soils, with very little internal drainage and active surface runoff. Finally, the geotechnical characteristics observed indicate that this area presents materials with a high load-bearing capacity although, due to the degree of fracturing and slate in the area, the existence of weak zones is possible.

Area III: the characteristic materials are a series of isolated quaternary outcrops, corresponding to the alluvial ones, with granular materials and with a variable percentage of silt and clay, generally loose, linked to the fluvial network, not presenting lithological problems. In terms of geomorphological characteristics, it is characterised by a flat topography with good stability. In terms of hydrogeological characteristics, the materials are generally permeable with variable internal drainage due to intergranular porosity, which varies according to the percentage of clays. Surface runoff is acceptable to favourable, with alluvial deposits being the worst. Finally, the geotechnical characteristics have a bearing capacity ranging from medium to low, which will depend on the lithological composition and the position of the water table.

4.2. Natural Hazard Cartography

This mapping has been carried out on the basis of the interpretation of the previous geotechnical mapping and considering the actual erosion mapping (Figure 11) [43]. In this way, it is possible to establish the different problems that may arise most frequently, as well as the determining aspects of their evaluation.

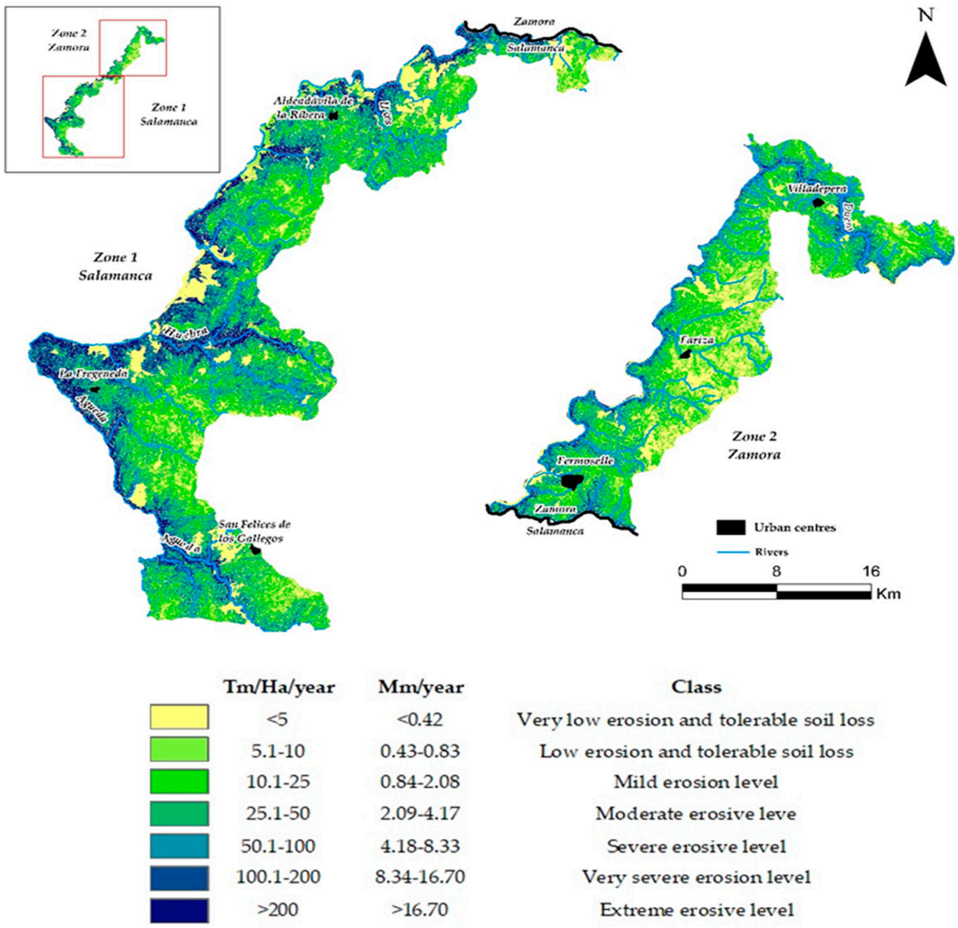


Figure 11. Actual erosion map.

In the Arribes del Duero Natural Park there are five types of problems: hydrological problems; lithological and geomorphological problems; geomorphological and hydrological problems; geomorphological and lithological problems; and geotechnical problems.

The types of problems observed in the study area and their associated mapping are described as follows (Figure 12):

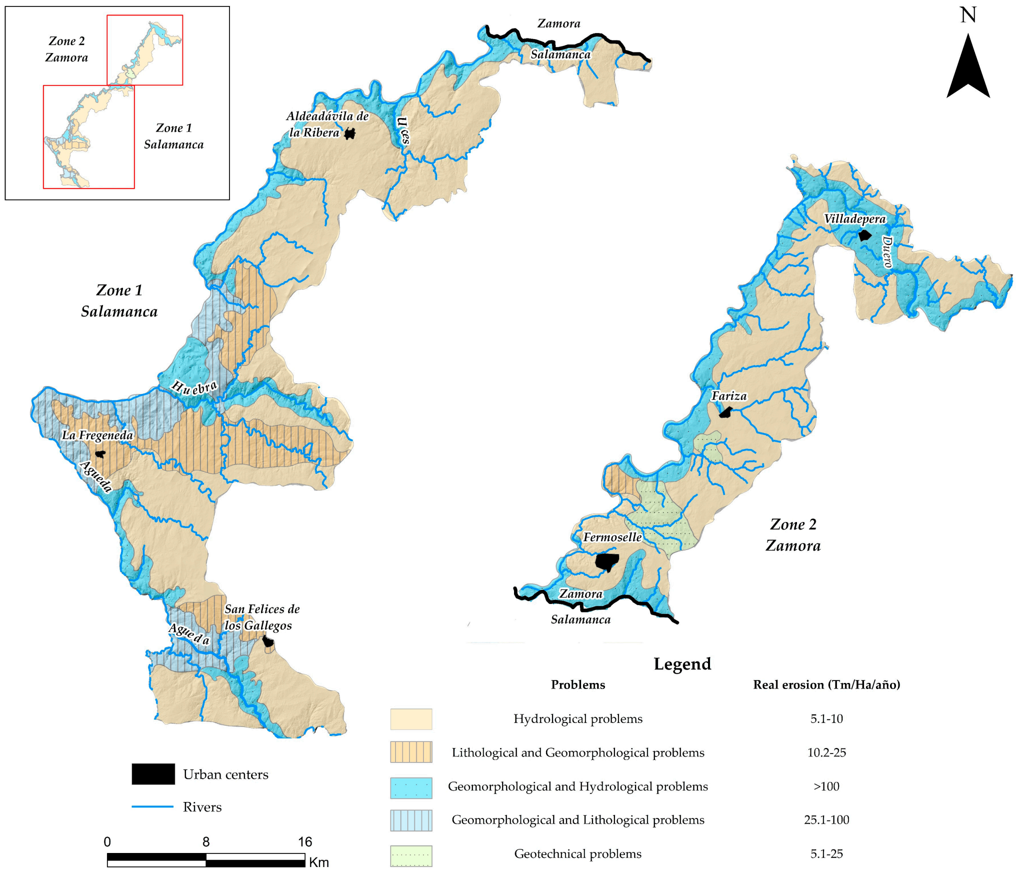


Figure 12. Hazard cartography.

Hydrological problems: these occur in a large part of Area I_1 and I_2, whose materials are impermeable, with semi-permeable granular coatings. As far as surface runoff is concerned, it is active in a large part of the area, therefore, the possible problems would be very localised. In terms of erosion rates, these areas are considered tolerable soil losses (5.1–10 Tm/Ha/year), thanks to the fact that the existing vegetation is of high density and herbaceous cover and, in addition, with more developed soils whose intrinsic characteristics provide greater protection against possible erosion. For example, in the locality of Trabanca, we can observe a blockfield followed by a lehm, the first one composed of granitic boluses that have resisted weathering, whereas the second one is alteration material with a sandy appearance, formed as a consequence of the penetration of water through the fractures in the granites, favouring the processes of chemical and physical weathering (hydrolysis, hydroclastia, dissolution, etc.) (Figure 13A).

Lithological and geomorphological problems: lithological problems predominate, due to the fact that, although the materials are impermeable, there may exist planes of weakness such as diaclases, fractures or slate that cause instability but under the action of man. In the case of quartzite levels, there are excavation and drilling problems due to their hardness. In terms of geomorphological problems, these occur in areas with a slight slope and average erosion rates (10.1–25 Tm/Ha/year). Unlike the previous ones, the soils are of medium development, with a lower percentage of herbaceous cover, giving the soil less protection, which is why the reason for noticeable greater erosion losses. For example, the Sierro de Peñahorcada is formed by the filling of old fractures with quartz, highlighting the landscape and presenting a very good geotechnical resistance and quality of the massif (Figure 13B).

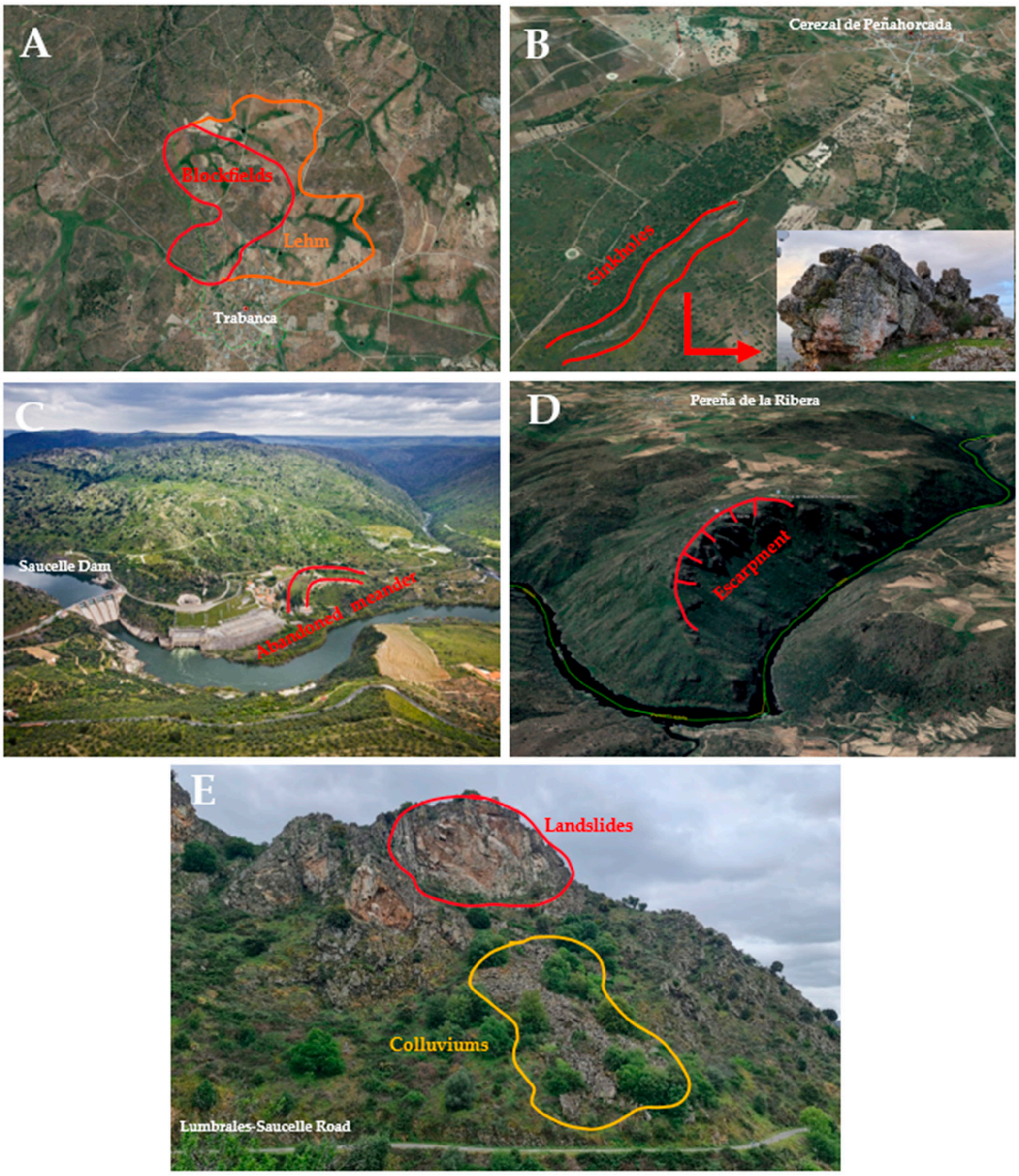


Figure 13. (**A**) Blockfield and lehm de Trabanca; (**B**) Sierro de Peñahorcada with quartz dyke; (**C**) abandoned meander at Presa de Saucelle; (**D**) rotational landslide at Pereña; (**E**) landslides.

Geomorphological and hydrological problems, which correspond to Areas I_1 and I_2 but are located in areas of steep slopes, caused by the confinement of the fluvial network, especially of the Duero river. There may be problems of instability under the action of man, favoured by the presence of covering materials of an arcosic nature, with a greater or lesser clay content, and also by surface infiltration of runoff water.

In terms of erosion rates, we find values of over 100 Tm/Ha/year, which is considered a severe-extreme erosive level, largely due to the high slopes, which is why geomorphological problems predominate over hydrological ones and, furthermore, with vegetation of little protective power and low coverage percentages, thus further accentuating the vulnerability of the soils which are already underdeveloped. For example, as a consequence of the silting up of the Duero river and erosive processes, we can observe abandoned meanders such as the Saucelle dam (Figure 13C) or also rotational and gravitational landslides (Figure 13D) and landslides (Figure 13E).

Geomorphological and lithological problems, with materials from Area II, also located in areas of steep slopes topography and due to the presence of planes of weakness caused by slate, diaclases, faults, etc. All of this conditions the possible existence of instabilities under the action of man, due to the fact that it breaks the complicated established equilibrium. With regard to erosion rates, it is possible to observe areas with moderate and medium erosion levels, with values between 25.1 and 100 Tm/Ha/year, located in areas with lower slopes, with respect to the previous one, where soils of intermediate development predominate, with more clay content and a vegetation with greater coverage, making them less susceptible to erosion.

Geotechnical problems are observed in a small area near Fermoselle and correspond to Quaternary materials, i.e., Area III. These are loose, permeable, sandy materials with a low load capacity. The erosion levels in this area are characterised by low to medium erosion levels, with values between 5.1 and 25 Tm/Ha/year, with poorly developed soils and dense vegetation and acceptable coverage, in addition to low slopes.

5. Conclusions

At present, special planning comprises numerous GIS resources (orthophotos, metric and centimetric lidar models, the use of UAVs, etc.) which, implemented in GIS, allow a simple analysis of the different natural processes. Geotechnical mapping makes it possible to establish basic information prior to decision-making by means of natural hazard mapping. In this way, geotechnical mapping has been carried out in the Arribes del Duero Natural Park, based on the detailed analysis of the lithological, hydrogeological and geomorphological characteristics and, subsequently, the natural hazard mapping, focused on the correct territorial planning.

In the geotechnical mapping, we have differentiated three geotechnical areas, grouped according to homogeneous lithological, hydrological and geomorphological characteristics. Area I_1, made up of granitic, impermeable and semi-permeable rocks, with a high load capacity, has favourable to acceptable geotechnical characteristics. Area I_2 is made up of gneisses with low permeability, topographically located in stable areas, with a high load capacity in geotechnical terms. On the other hand, Area II, with slate type rocks, impermeable, with variable topography (flat and sloping areas), with high load capacity. Finally, Area III, made up of a series of Quaternary outcrops, with high and medium permeability, with medium to low bearing capacity.

In the natural hazard mapping, five types of problems can be listed as follows: hydrological problems; lithological and geomorphological problems; geomorphological and hydrological problems; geomorphological and lithological problems; and geotechnical problems. These problems have been classified and distinguished according to their lithological, hydrological and geotechnical characteristics and, in addition, the real erosion rates have been taken into account. The hydrological problems are the most extensive, occupying most of the eastern part of the study area, coinciding with the flat areas. The lithological and geomorphological problems are concentrated between the town of La Fregeneda and the river Huebra, with higher slopes. The geomorphological and hydrological problems are located in the steeper areas, i.e., in the Duero river canyon or in the valleys of the tributaries such as the Huebra, Águeda or Tormes. Likewise, in areas of steep slopes, although with valleys that are not embedded, such as in the area around La Fregeneda. Finally, the geotechnical problems are the least extensive, being located in a limited area to the south of Fermoselle. Finally, it is important to highlight that the geotechnical mapping would allow us to delimit areas of recommendations and limitations of uses in terms of construction activities and the mapping of natural hazards, which will allow us to establish a potential risk mapping method for rational and sustainable territorial planning.

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sion, A.M.M.-G.; project administration, A.M.M.-G.; funding acquisition, A.M.M.-G. All authors have read and agreed to the published version of the manuscript.

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