UNIVERSIDAD POLITÉCNICA DE MADRID

E.T.S. DE INGENIERÍA AGRONÓMICA, ALIMENTARIA Y DE BIOSISTEMAS

DPTO.PRODUCCIÓN AGRARIA/ DPTO. MATEMÁTICA APLICADA

**Quantifying patterns of complexity controlled
by parent material at different spatial scales:
from drainage network architecture at
landscape scale to soil texture.**

**A hydropedologic research conducted on
wine regions of the Douro river basin.**

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Ingeniero Agrónomo

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Para la obtención del título de Doctor por la Universidad Politécnica de Madrid

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*A todos los que con su colaboración o
apoyo han hecho posible este documento, gracias.*

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ABBREVIATIONS

Abbrev	Abbreviation (Synonyms)
a	Reference density
ANOVA	Analysis of Variance
BEI	Balanced Entropy Index
BSD	Bonferroni Significant Difference
D	Fractal box-counting dimension (FD)
DD	Drainage density
DEM	Digital Elevation Model
DO Arribes	Designation of Origin Arribes
DTM	Digital Terrain Model
E	Elevation
FAT	Flow accumulation threshold
FD	Fractal box-counting dimension (D)
GIS	Geographic Information System
GMP	Geological Map of Portugal, 1/50,000
H	Shannon's entropy
HI	Hypsometric Integral
I	Igneous rocks (P)
IGN	Instituto Geográfico Nacional de España [©]
LG	Lithological Group
LiDAR	Light Detection and Ranging
LMU	Lithological Map Unit (LU)
LSD	Least Significant Difference
LU	Lithological Unit (LMU)
M	Metamorphic rocks
MAGNA50	National Geological Map of Spain, 1/50,000
P	Plutonic rocks (I)
p	p-value
PSD	Particle-size distribution
R²	Coefficient of determination
RD Douro	Região Demarcada do Douro
S	Sedimentary rocks
SMU	Soil Map Unit
Std. Dev.	Standard deviation
STU	Soil Taxonomic Unit
USDA	United States Department of Agriculture
X_UTM	Coordinate X in the Universal Transverse Mercator projection
Y_UTM	Coordinate Y in the Universal Transverse Mercator projection
Λ	Lacunarity

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RESUMEN

La hidroedafología es una ciencia interdisciplinar que aborda el estudio de la interacción entre las propiedades y los procesos edafológicos e hidrológicos, con el objeto de incrementar el conocimiento existente sobre la influencia del suelo en los procesos hidrológicos y sobre los efectos hidrológicos en la formación, variabilidad y funciones del suelo. Este enfoque multidisciplinar es imprescindible para resolver retos medioambientales actuales tales como el uso sostenible de la tierra, la gestión de los recursos hídricos, o el desarrollo de sistemas de agricultura integrada entre otros.

Compartiendo la visión de otros autores, en este trabajo se define el paisaje como un sistema complejo donde las interacciones intermitentes a escala milimétrica entre sus múltiples componentes, que están controladas por una mezcla de fuerzas deterministas y componentes aleatorios, generan patrones de complejidad emergentes a escalas mayores, que aportan información novedosa sobre el funcionamiento interno del sistema. La teoría de los sistemas complejos sostiene que los sistemas con muchos grados de libertad, como el sistema del paisaje, evolucionan exportando desorden hasta que alcanzan el máximo nivel de organización que les permiten los factores condicionantes del sistema.

Las características geológicas del paisaje son un elemento de gran importancia que puede catalogarse como uno de los factores condicionantes del sistema que dirigen su evolución y la emergencia de patrones de complejidad. Algunos de estos patrones emergentes han sido cuantificados con éxito en este trabajo mediante medidas de complejidad, como la dimensión fractal box-counting y el índice de entropía equilibrado (BEI, por su siglas en inglés), que han permitido identificar el control que ejerce el material parental en la zona de estudio sobre las estructuras internas del paisaje. El área de estudio está compuesta por dos regiones vitícolas situadas en la cuenca hidrográfica del Duero, que son: la región española incluida en la Denominación de Origen Arribes (DO Arribes), y la región portuguesa comprendida dentro de la Região Demarcada do Douro (RD Douro). Los materiales parentales presentes en estas regiones son principalmente rocas metamórficas (gneises, filitas, grauvacas, pizarras, esquistos, y cuarcitas), y rocas ígneas (mayoritariamente rocas graníticas).

La influencia del material parental sobre la estructura del paisaje ha sido estudiada a escala de paisaje y a escala milimétrica, en la arquitectura compleja de las redes de drenaje y en las distribuciones de masa según los distintos tamaños de partículas en el suelo, respectivamente. El efecto de la litología sobre las redes de drenaje condiciona la aparición de diversos patrones de redes de drenaje que han sido tradicionalmente clasificados de modo cualitativo, según la apariencia de la configuración de sus canales, como dendríticos, paralelos, rectangulares, etc. Esta discriminación cualitativa entre distintos patrones de drenaje ha sido ampliamente utilizada por los geomorfólogos para identificar visualmente y delimitar zonas con materiales geológicos diferentes durante el proceso de elaboración de cartografía geológica. Frente a la tradicional caracterización cualitativa de las redes, en el Capítulo 1 se cuantifica a través de la dimensión fractal box-counting, la estructura jerárquica de las redes de drenaje y la distribución espacial de los subconjuntos representados dentro de esas redes por los canales de primer orden, lo que ha permitido aportar evidencias cuantitativas de la influencia del material parental sobre estos patrones de complejidad a escala de paisaje. Este control litológico sobre las redes de drenaje es la base conceptual del modelo de clasificación estadística, propuesto en el Capítulo 2, para la identificación del material geológico del paisaje a partir del análisis de redes de drenaje generadas automáticamente desde un modelo digital del terreno LiDAR de media resolución.

En contraste con la estructura de las redes de drenaje, que ha sido analizada a escala de paisaje, el control litológico sobre las propiedades del suelo ha sido estudiado a escala milimétrica a través del índice de entropía equilibrado, que cuantifica la heterogeneidad de la distribución del tamaño de partículas del suelo. Considerando que tanto la estructura de la red de drenaje como la heterogeneidad en la distribución del tamaño de partículas son consecuencia a distinta escala de los mismos factores condicionantes del sistema, el Capítulo 3 explora la relación cuantitativa entre ambos patrones de complejidad, cuantificados a través de la dimensión fractal box-counting y el índice de entropía equilibrado, respectivamente.

El estudio sobre la influencia del material parental en la heterogeneidad de la textura del suelo, mostrado en el Capítulo 4, propone un método de agregación de la información contenida en el mapa de suelos 1/25,000 de la zona de estudio, para la obtención y asignación de un valor representativo del índice de entropía equilibrado a cada unidad litológica del mapa. El método de agregación propuesto tiene en cuenta

todos los niveles de información contenidos en un mapa de suelos (horizonte, perfil, unidad taxonómica, unidad cartográfica), y todas las interrelaciones y distribuciones de frecuencia entre dichos niveles de información. Los valores del índice de entropía equilibrado obtenidos para los suelos desarrollados sobre rocas graníticas y metamórficas permiten constatar cuantitativamente, en nuestra zona de estudio, cierto control litológico sobre la heterogeneidad de la textura del suelo.

Los resultados obtenidos evidencian la influencia del material parental sobre distintos patrones de complejidad relacionados con el movimiento del agua a través del paisaje, lo que sugiere que las áreas con material parental homogéneo podrían ser usadas como unidades funcionales en la modelización de cuencas hidrológicas. Esta hipótesis deberá ser demostrada o rechazada a través de futuros trabajos que incluyan datos hidrológicos y meteorológicos en el análisis del sistema.

SUMMARY

Hydropedology is an emerging interdisciplinary science that studies interactive pedologic and hydrologic processes and properties, and aims to better understand the pedologic controls on hydrologic processes, and the hydrologic impacts on soil formation, variability and functions. This multidisciplinary approach is strongly required to address environmental issues of societal importance such as sustainable land use, watershed management, or integrated agricultural systems, among others.

Sharing the vision of other authors, this study observes landscapes as complex systems where multiple interactions at micro level, controlled by a mixture of deterministic forces and random components, create emergent patterns at macro level that provides novel information about the system. Complex systems theory suggests that systems with many degrees of freedom, such as landscape systems, evolve exporting disorder until they reach the maximum level of organization permitted by the system constraints.

Geology is an essential landscape characteristic that can be viewed as a system constraint influencing the landscape evolution and the complex structure of the emergent patterns. The quantification of these emergent patterns using complexity measurements, such as the fractal box-counting dimension and the balanced entropy index, has enabled to confirm in the study area the main role of parent material in complex structures within the landscape system. The study area is conformed of two wine regions located within the Duero river basin; the Designation of Origin Arribes (DO Arribes), in Spain; and the Região Demarcada do Douro (RD Douro), in Portugal. The parent material in the study area encompasses metamorphic rocks (gneisses, phyllites, greywackes, shales, schists and quartzites) and igneous rocks (majorly granitic rocks).

The influence of parent material within the landscape system has been studied in both the complex architecture of drainage networks at landscape scale and in the mass distribution of soil particle sizes at micro scale. The lithologic control on drainage networks determines the emergence of different drainage patterns that have been traditionally classified as dendritic, parallel, rectangular, etc. depending on the geometric structure of their streams. These qualitative classes have been widely used by

geomorphologists for visual discrimination of different materials in geological mapping. In Chapter 1, the hierarchical structure of drainage networks, and the subset represented by first-order streams of the network are effectively quantified using the fractal box-counting dimension. This chapter shows quantitative evidences about the lithologic control on this pattern of complexity at landscape scale. The influences of parent material on drainage networks are used in Chapter 2 to propose a statistical classification model for the identification of the underlying type of rock, based on the analysis of drainage networks automatically extracted from medium-resolution LiDAR digital terrain models.

In contrast with the drainage networks that were studied at landscape scale, the lithologic control on soil system has been explored at micro scale, using the balanced entropy index to quantify the heterogeneity of the soil particle size distributions. Considering that both patterns of complexity are the result of the same system constraints, Chapter 3 investigates the quantitative relationship between the hierarchical structure of the drainage networks and the soil texture heterogeneity, quantified by the fractal box-counting dimension and the balanced entropy index, respectively.

A deeper analysis of the lithologic control on the heterogeneity of the soil particle size distributions within the landscape system is shown in Chapter 4, where all the levels of information contained in the soil map 1/25000 of the study area (horizon, profile, taxonomic unit, and map unit) along with their interrelations and frequency distributions, are taken into account in the aggregation method used for assigning a representative value of soil texture heterogeneity to each lithological unit with homogeneous parent material. Differences found in the values of the balanced entropy index obtained for soils developed on metamorphic and granitic rocks allow to confirm the lithologic control on soil texture heterogeneity in the study area.

Results evidence the influence of parent material on complex structures related to the water movement across the landscape at different scales, suggesting that areas of homogeneous parent material could be used as functioning hydrologic units in watershed modeling. Further research including hydrological and meteorological data should explore this suggestion.

GENERAL INTRODUCTION

A multidisciplinary systems approach is required for addressing environmental issues of societal importance such as nonpoint source pollution, watershed management, natural disasters prevention, integrated agricultural systems, precision farming, sustainable land use, and restoration and preservation of ecosystems, among others.

Hydropedology is an emerging interdisciplinary science that studies interactive pedologic and hydrologic processes and properties in the Earth's Critical Zone, which is defined as the thin layer of the Earth's surface and near-surface terrestrial environment from the top of the vegetation canopy (or atmosphere-vegetation interface) to the bottom of the weathering zone (or groundwater-bedrock interface) (National Council Research, 2001). Environmental processes within the Earth's Critical Zone, such as mass and energy exchange, soil formation, streamflow generation, and landscape evolution are key processes to sustaining biodiversity and humanity (Lin et al., 2011; Field et al., 2015).

Soil and water interaction creates the fundamental interface between the biotic and abiotic systems, and hence is a key determinant of the state of the Earth system. Hydropedology aims to understand pedologic controls on hydrologic processes and properties, and hydrologic impacts on soil formation, variability, and functions.

The unifying precept for hydropedology is the landscape water flux, which encompasses the source, storage, flux, pathway, residence time, availability, and spatiotemporal distribution of water (and the transport of chemicals and energy by flowing water) in the soil under both saturated and unsaturated conditions from microscopic to global spatial scales and encompassing infinitesimal to geological timescales (Lin et al., 2006).

One of the factors promoting hydropedology at the present time is the landscape perspective, which is a key point to address soil-water interactions across multiple scales. This landscape perspective implies managing the inherent variability in the field, the scale transfer from laboratory or small plot scales to the larger field and watershed scales, and the requirement of meaningful experimental design and data analysis to address the landscape complexity.

Landscape as a complex system

Landscapes are composed by a large number of mutually interacting parts exchanging energy, matter and information among their multiple components and with the environment. Landscapes take water from the atmosphere in a distributed and intermittent way, store it in the soil and release a portion into a drainage network of stream channels where the flux is concentrated and delivered gradually to the outlet. Along this pathway water interacts with the landscape putting mineral constituents into solution, transporting particles and chemicals, participating of the animal and plant life, and reshaping the landscape through entrainment and deposition, conditioning the soil system. The movement of a single water drop across the landscape is driven by a mixture of deterministic forces and random components that do not enable the modeling and prediction of its route. However, the joint effect of all the water drops interacting within the landscape, along with the rest of interactions taking place at the micro-level, creates emergent patterns at the macro-level (e.g. drainage networks, soil layering, particle size distribution) that provide novel information about the landscape system as a whole. This approach on landscapes as complex systems shares the vision of others authors (Ibañez et al., 1990; McBratney, 1992; Phillips, 1998; Rodríguez-Iturbe and Rinaldo, 1997) who applied non-linear dynamical systems and complex systems theory in the context of soil science, geomorphology and river basins.

Behind the formation of structures or the emergency of patterns at the macro level, is the theory of self-organized criticality, where geophysical systems are viewed as systems with many degrees of freedom which evolve to a marginally stable state that represents the maximum level of organization permitted by the boundary conditions of the system. When systems are perturbed from these states, they evolve naturally back to the state of marginal stability or critical state, that covers a wide range of temporal and spatial scales. A characteristic of the structures that emerge when the system reaches its higher organization level is fractality, or the absence of natural length scale along with self-similarity across scales, which is reflected in the power laws describing the probability distributions of their geometric properties.

The abstract concept of the organization level, which has been succinctly introduced above, is hardly manageable or measurable. However, this level of

organization is reflected in the geometric properties of the emerging hierarchical structures of the system and also in the complexity or heterogeneity of the related distributions, which are both quantifiable using the appropriate tools.

Role of parent material in the landscape system

The concept of parent material used in this work has been taken from the Hans Jenny's factors of the soil formation model, that considers soil as a function of climate, organisms (biosphere), topography (geomorphology, relief and drainage), parent material (geology), and time (Jenny, 1941). Soil forming factors can be classified in *site factors* (topography and parent material), *flux factors* (climate and organisms), and the *time factor*. According to this model, site factors are affected by flux factors over the time in the continuous process of soil formation.

The definition of parent material is not immediately assumed with the bedrock geology of the site because in numerous cases the parent material of the surficial soil is not the result of the weathering processes of the underlying bedrock geology (e.g. aeolian sediments on igneous rocks, volcanic ashes on fluvial terraces). Jenny (1941) avoided special reference to the strata below the soil which may or may not be the parent material, defining parent material as the initial state of the soil system. Upscaling this concept from the soil scale to the landscape scale, the concept of parent material is assumed in this work as the initial state of the landscape system.

Jenny (1941) found serious difficulties in the quantitative evaluation of the parent material influence on soil, and recognized that the greatest obstacle is assigning numerical values to different types of parent materials. He tried to record the properties of different types of parent material in a single number that would encompass chemical composition, mineralogical constitution, texture, and structure of the rock, but accepted that it was only possible to find correlations between soil properties and specific rock properties such as lime content, permeability, etc.

If parent material is the initial state of the landscape system, it might also be considered as part of the well-defined bounds of this system determining that its complex and irregular development is governed by an attractor and exhibits order or high levels of organization across the scales.

The influence of parent material in soil-water interactions within the landscape system is quantified in this work measuring both the geometric properties of the structures of the landscape system using fractal parameters, and the heterogeneity of their related distributions using entropy-derived parameters based on the information theory (Shannon, 1948a,b). In order to do this, the hierarchical structures and related distributions of the landscape system selected in this work are intimately connected to the landscape water flux. They are the drainage networks of the landscape that represent the pathway of surficial waters across the landscape (Rodriguez-Iturbe and Rinaldo, 1997) and the soil particle-size distributions or soil textures which are related to the storage and release of water in soils (Saxton et al., 1986; Saxton and Rawls, 2006).

Due to the geological characteristics of the studied areas where crystalline rocks are major and the development of the pedogenetic processes is very poor, the terms parent material, bedrock lithology, and geological material have been used indistinctly along the work.

What the reader will find in this work

The present work constitutes a hydropedologic research developed on wine growing regions of the Duero river basin, and it addresses to a greater or lesser extent the five key issues within the holistic conceptual framework for integrated hydropedologic studies suggested by Lin et al. (2006).

1. Quantification of hierarchical structures of soil and hydrologic systems

As cited above, the complexity of a system could be reflected in the geometry of its structures or in the heterogeneity of their related distributions. This work emphasizes the quantification of patterns of complexity in both soil and hydrologic systems, aiming to identify lithologic controls on those patterns.

The influence of parent material on the hydrologic system has been quantified measuring the complexity reflected in the geometry of its hierarchical structures. Due to the recognition of the fractal nature of drainage networks (Rodriguez-Iturbe and Rinaldo, 1997) the complexity of the hierarchical structure of drainage networks at landscape scale is quantified in this work using fractal parameters such as fractal box-

counting dimension (Russel et al, 1980), and lacunarity (Borys, 2009). The box-counting dimension proposes a systematic measurement that applies to any structure in the plane and can be readily adapted for structures in space. For obtaining the fractal box-counting of any structure, the structure is covered by a grid of side r and the number of grid boxes containing it is counted $N(r)$. The value of r is halved in successive steps ($1, 2, \dots, i$) and through the counting of the occupied boxes a series of N_i values is obtained (Fig. 0.1).

Fig. 0.1: Illustration of the box-counting procedure, adapted from Cámara et al. (2015)

Once a grid box size is established as the reference box size ($r = r_1$), the size factor of the successive steps is calculated as $s_i = r_i / r_1$. As r decreases to a threshold value the following relation converges to a finite value defined as box-counting dimension D .

$$D \approx \frac{\log N_i}{\log \left(\frac{1}{s_i} \right)} \quad (1)$$

When the box size is halved in every step and the fractal dimension is equal to D , the number of occupied boxes increases by a factor of 2^D in any step. Another fractal parameter used along with the box-counting dimension in this work to characterize the geometric properties of hydrologic patterns is the lacunarity ($\mathcal{A}$). To estimate the lacunarity the histogram of grid boxes of size r not covered by the analyzed structure within grid boxes of side R ($R > r$) needs to be calculated. Lacunarity is characterized in

this work by statistical moments. According to Borys (2009), lacunarity (Λ) can be defined as the ratio of two expectation values

$$\Lambda = \frac{E[X^2]}{E[X]^2} \quad (2)$$

where X is the variable describing the number of empty grid boxes of size r within the grid boxes of side R . Both parameters, D and Λ , are used in this work to characterize drainage networks and to establish quantitative relationships between drainage networks and specific subsets of their hierarchical structures such as first-order streams. The quantification of these geometric patterns of complexity has enabled the proposal of a statistical classification model for identifying the underlying parent material based on hydrologic structures.

On the other hand, within the soil system, this work quantifies the pattern of complexity reflected in the heterogeneity of the soil particle size distribution attached at the micro scale. Mathematically, the soil particle-size distribution or soil texture might be considered as a continuous mass particle-size distribution μ supported in the interval of grain sizes. Limited information on soil texture is usually determined over a list of size ranges that covers all the sizes present in the sample. Grains sorted according to the size thus appear distributed into size classes $J_1, J_2, \dots, J_k$ defined by those size ranges. Different methods of analysis may provide the mass fractions $p_1, p_2, \dots, p_k$, respectively. The Shannon's entropy (Shannon, 1948a,b) of the partition is defined by

$$H = - \sum_{i=1}^k p_i \log p_i \quad (3)$$

Shannon's entropy is an information-theoretical parameter that may be suitably interpreted as a measure of the complexity of a distribution. In fact, entropy has already been proposed in the life sciences as a plausible quantity of biodiversity (Margalef, 1958) in the sense of evenness or heterogeneity of the diversity of species in an ecosystem, and also as measurement of pedodiversity (Ibáñez et al., 1998; Martín and Rey, 2000). Shannon's entropy of heterogeneity does not take into account the length of the size intervals which is, in fact an important issue. Shannon's entropy serves as a good measure of evenness, if all class intervals are equal. Otherwise, the entropy may

become a distorted measure of evenness. The typical representation of soil texture in terms of clay, silt, and sand contents employs size ranges <0.002 mm, 0.002 to 0.05 mm, and 0.05 mm to 2 mm, respectively, according to the USDA soil texture classification. This results in extremely unequal class sizes of 0.002 mm for clay, 0.048 mm for silt, and 1.95 mm for sand. Martín et al. (2005a) proposed to normalize the Shannon entropy value with a multiplier that explicitly takes into account the differences in class sizes:

$$\beta = -\frac{H}{\sum p_i \log \varepsilon_i} = \frac{\sum p_i \log p_i}{\sum p_i \log \varepsilon_i} \quad (4)$$

in which β is the Balance Entropy Index (BEI), and ε_i is the proportion of the i -th class size interval in the total range of sizes. Theoretically, β ranges between 0 and 1 for any distribution: the closer to 1 the value of β the more even the distribution. $\beta = 0$ corresponds to the most uneven distributions, where all the mass is concentrated in a single size interval, while $\beta = 1$ corresponds to the most even distribution, in which the mass inside each interval is proportional to each size interval.

Fig. 0.2. BEI computations in the USDA textural triangle (Cámara et al., 2016b)

For the USDA soil texture classification with the clay, silt and sand categories ($i = 1, 2, 3$), $\varepsilon_1 = 0.002/2 = 0.001$, $\varepsilon_2 = 0.048/2 = 0.024$, and $\varepsilon_3 = 1.950/2 = 0.975$. Using

the proportions of clay, silt, and sand denoted by p_i , one can compute the balanced entropy from Eq. (4) for any texture defined by clay, silt and sand contents. Results of such computations are shown in the USDA textural triangle in Fig. 0.2. Note that the values of β approach unity at the rightmost corner of the textural triangle. Inside the textural triangle, the balanced entropy tends to increase as sand content increases. The balanced entropy provides a continuous parameterization within the textural triangle. Besides the natural use of the BEI for the characterization of heterogeneity, Martin et al. (2005b) showed that the balanced entropy index may be a promising approach to improve the accuracy of estimated soil hydraulic properties, and suggested that the BEI might be a natural index for the packing arrangement of soil particles. In this work the BEI is used to quantify the soil texture heterogeneity aiming to explore the influence of parent material in pattern of complexity at micro scale, and to identify quantitative relationships between pattern of complexity at different scales.

2. Identification and prediction of functional patterns

Identification of patterns related to the storage, release, pathway and residence time of the landscape water is needed to subdivide landscapes into similarly functioning hydrologic units, which is crucial for a realistic modeling of the hydrologic processes within the landscape.

Drainage networks, which represent the pathways of the surficial water along the landscape, can exhibit different patterns depending on the geological properties of the underlying material. Aiming to analyze the influence of parent material on these drainage patterns, the hierarchical structure of the drainage networks has been quantified in several areas with homogeneous parent material. Lithologic control on drainage patterns proves to be so strong in our study area that it allows to establish a statistical classification model to predict the underlying parent material from quantitative description of drainage networks based on fractal analysis.

On the other hand, soil particle size distribution is known to be a leading soil property affecting soil hydraulic properties and it has been commonly used as predictor variable in most of the pedotransfer functions proposed for estimating soil water characteristics such as the soil water storage and release. This work identifies patterns of complexity in the heterogeneity of soil particle size distributions controlled by parent material. It represents a key point of this hydropedological research because the

heterogeneity of soil particle size distributions measured by means of the Balanced Entropy Index seems to be an effective tool to estimate the storage and release of water in different soils. This index could represent a step towards a better understanding of the pedologic controls on the hydrologic processes, and in the future, it could be a crucial tool for translating soil data into hydrological information. In order to assign a characteristic value of soil texture heterogeneity to a specific parent material, it is preferable to take into account in the estimation all levels of information in soil survey databases (soil horizons, soil layering, soil taxonomic units and soil map units) and their interrelations, rather than surficial soil data. However, in this work it has been possible to establish quantitative relationships between the complexity of the drainage patterns at landscape scale and the heterogeneity of soil texture at pedon scale using surficial soil data.

Lithologic control on patterns related to the landscape water flux such as those identified and quantified in this work suggests that areas of homogeneous parent material could be potentially considered as similarly functioning hydrologic units. Further research on this direction would confirm this suggestion.

3. Bridging multiple scales

Various authors (Kalma and Sivapalan, 1995; Pachepsky et al., 2003) agree that translating information about soil and hydrological properties and processes across scales represents a major theme in contemporary soil science and hydrology.

A motivating challenge is to transfer results from laboratory studies using soil cores to soil map units in the field, and then to watershed, regional, and global scales. This challenge has been addressed in this work to assign a characteristic value of soil texture heterogeneity to areas of homogeneous parent material that usually encompasses several soil map units at the study scale. In this case, the soil map 1/25,000 of the studied regions (Gómez-Miguel et al., 2011a,b) has been the basis of the proposed aggregating method for the values of soil texture heterogeneity. This method allows obtaining a characteristic value for entire areas ranging from one to hundreds of square kilometers, weighting punctual values by using the known frequencies and relationships among soil samples, soil horizons, effective depths, soil taxonomic units, soil map units and areas of homogeneous parent material. The proposed method is in line with the 'scaleway' approach suggested by Vogel and Roth (2003) for predictive modeling of

flow and transport through the soil system at any scale, which assumes that at any scale of interest there is a spatial structure where heterogeneities at finer scales may be replaced by an average effective description at coarser scale.

As part of this hydropedologic research, the interrelation within the landscape system between drainage patterns at landscape scale and soil heterogeneity patterns at micro scale has been investigated in areas of homogeneous parent material. This approach follows the ideas expressed by Ibáñez et al. (1990) about a structural correspondence between the spatial organization of the surficial drainage system and that of the soil properties distribution at different scales, which are supported on the consideration that coevolution of both levels of organization is directed towards an increase in complexity under the same system constraints that generates interrelated patterns of complexity at all spatial scales.

4. Integrated models and databases

Determining what is important to system behavior has a major importance in any modeling application. Modeling the water flow across the landscape system requires an in-depth understanding of the different processes that become dominant in the water flow at different temporal and spatial scales. At micro scale, capillarity and laminar flow through the pore space control the water flow, but at catchment scale the flow is routed through the drainage network. Lin et al. (2006) suggested that quantitative soil-landscape relationships can improve the prediction accuracy of pedotransfer functions and hydrologic models at landscape level. As parent material plays a key role within the soil-landscape relationships, this work quantifies patterns of complexity controlled by parent material at both soil particles scale and landscape scale, aiming to obtain quantitative parameters useful for enhancing simulations of system response. As the balanced entropy index used in this work has been recognized as a promising tool to improve the accuracy of estimated soil hydraulic properties, this work proposes an innovative use of soil survey data for quantifying the environmental influences on this balanced entropy index, which might have interesting applications in hydrologic modeling.

This work tries to relate different scales and scenarios of the landscape system by finding quantitative evidences on geometric structures and probability distribution attached at very different scales. To address an ambitious research with these

characteristics it is crucial to have available global data of the landscape system that encompasses exhaustive data of the systems considered as characteristics, attributes or components of the landscape system such as the landscape topography, the lithological properties, the drainage network architecture, the soil distribution, the soil layering and the particle size distribution. The mere identification of quantitative relationships among different scales that may help understand the system requires of quality databases capturing as much landscape variability as possible. It is noteworthy that the thesis' author has worked exhaustively in the generation of most of the databases used in this research. He dedicated several months in the identification and digitization of the drainage network used by Cámara et al. (2013, 2016a), and he participated during three years as soil surveyor in the team that carried out all the field work involved in the creation of the soil maps 1/25,000 (Gómez-Miguel et al., 2011a,b) used along this research.

This work also represents an example of the database interoperability and the interdisciplinary approach needed to develop a hydropedologic research. The hydrologic structures analyzed in this work have required translation of information from aerial photograms, scale 1/18,000 and raster topographic databases with 5 m-resolution into vector layers which are manageable and interoperable in geographic information systems. On the other hand, soil properties quantified from soil samples have been translated into regional scale using the soil map 1/25,000 database in order to provide quantitative parameters with potential application in hydrologic modeling. The required techniques for all these processes have demanded prior knowledge and expertise of the thesis's author in photogrammetry and photo-interpretation, data analysis and management, geographic information systems, soil mapping, soil physics, fractal theory, mathematical modeling and statistical analysis. This interdisciplinary approach has represented the major effort in this hydropedologic research.

5. Human Impacts

Land management practices and other human impacts modify the dynamics of soil and hydrologic properties. This research focuses in the influence of parent material in the pattern of complexity of hydrologic and soil systems, and thus, the human impacts have been only indirectly evaluated in this work as part of the environmental variability which could alter those patterns of complexity. However, the configuration

of the drainage networks and soil properties as soil texture at regional scale are extremely difficult to be modified from human scale. Nevertheless, land management practices are cited in this work, and their potential effects in the results are discussed.

Thesis's structure

After this introduction section, the core of this thesis is divided into four chapters that correspond to four publications in peer-reviewed journals signed by the thesis' author as first author. Following these four chapters, the work presents the section of conclusions where the achievement of the work's objectives is evaluated and some directions for further research are suggested.

Chapter 1 is entitled "Lithologic control on the scaling properties of the first-order streams of drainage networks: a monofractal analysis", and it was published in 2013 in *Vadose Zone Journal* 12 (Cámara et al, 2013). Chapter 1 explores the influence of parent material in the hierarchical structure of the drainage networks at landscape scale. The structure of the drainage networks and the spatial distribution of their first-order streams were characterized using fractal parameters such as fractal box-counting dimension and lacunarity.

Chapter 2 is entitled "Identification of bedrock lithology using fractal dimensions of drainage networks extracted from medium resolution LiDAR digital terrain models" and it was published in 2016 in *Pure and Applied Geophysics* 173 (Cámara et al., 2016a). The lithologic control on the drainage networks suggested in Chapter 1 is used in this chapter to propose a statistical classification model that uses the fractal box-counting dimension of the drainage networks to identify the underlying parent material. In contrast with the drainage network used in chapter 1, that was laboriously and time-consuming digitized manually after stereoscopic photo-interpretation of hundreds of aerial photograms, Chapter 2 explores and evaluates the automatic extraction of drainage networks at landscape scale from medium resolution topographic databases with lithological identification purposes.

Chapter 3 is entitled "Quantifying the relationship between drainage networks at hillslope scale and particle size distribution at pedon scale". It was published in 2015 in

Fractals 23 (Cámara et al., 2015). Considering both the fractal structure of the drainage networks and the soil particle size distributions as evidences or effects at different scales of the entropic level of the landscape system, this chapter explores the quantitative relationship between the fractal dimension of drainage networks at landscape scale and the balanced entropy index of surficial soil samples in areas of homogeneous parent material. This chapter relates hydrologic and pedologic patterns of complexity attached at different levels of the spatial scales range in the landscape system, bridging disciplines, scales and data.

Chapter 4 is entitled "Lithologic control on soil texture heterogeneity". Accepted for publication in 2016 in *Geoderma*, now it is currently in press (Cámara et al., 2016b). This final chapter explores the influence of parent material on the soil texture heterogeneity. In contrast with chapter 3, where soil texture heterogeneity is only estimated in surficial soil samples, in chapter 4 the lithologic control on the soil texture heterogeneity is evaluated using all the information levels contained in the soil map 1/25,000 of the study region: individual horizon properties, relationships between horizon thickness and effective depth on the soil taxonomic units, quantitative presence on the soil map units of the soil taxonomic units, and the diversity of soil map units within areas of homogeneous parent material.

GENERAL OBJECTIVES

The general goal was to evaluate the influence of parent material in patterns of complexity related to the landscape water flux at different spatial scales. The studied parent materials correspond to granitic and metamorphic rocks of the Duero river basin.

The specific objectives of this study were:

- i. To quantify patterns of complexity within the landscape system such as the hierarchical structure of drainage networks and the heterogeneity of the soil particle size distributions.
- ii. To investigate if those patterns of complexity could be useful for the quantitative identification of geological characteristics of the underlying material.
- iii. To explore in areas of homogeneous parent material the quantitative relationships between patterns of complexity of the landscape system attached at very different scales.
- iv. To propose innovative uses of available databases, such as digital terrain models and semi-detailed soil maps to bridge data and scenarios in order to provide novel information of the system.

CHAPTER 1.

LITHOLOGIC CONTROL ON THE SCALING PROPERTIES OF THE FIRST ORDER STREAMS OF DRAINAGE NETWORKS: A MONOFRACTAL ANALYSIS

ABSTRACT

The interrelation between bedrock lithology and the geometry of the drainage systems has been widely studied in the last decades. The quantification of this linkage has not been clearly established. Several studies have selected river basins or regularly shaped areas as study units, assuming them to be lithologically homogeneous. This study considered irregular distributions of rock types, establishing areas of the soil map (1/25 000) with the same lithologic information as study units. The tectonic stability and the low climatic variability of the study region allowed effective investigation of the lithologic controls on the drainage networks developed on the plutonic rocks, the metamorphic rocks, and the sedimentary materials existing in the study area. To exclude the effect of multiple in- and outflows in the lithologically homogeneous units, we focused this study on the first-order streams of the drainage networks. The geometry of the hydrologic features was quantified through traditional metrics of fluvial geomorphology and scaling parameters of fractal analysis, such as the fractal dimension, the reference density, and the lacunarity. The results demonstrate the scale invariance of both the drainage networks and the set of first-order streams at the study scale and a relationship between scaling in the lithology and the drainage network.

1.1. INTRODUCTION

Drainage networks have been studied in hydrology (De Bartolo et al., 2000), geology (Howard, 1967), and geomorphology (Montgomery and Dietrich, 1992). Each of these disciplines focuses on different drainage network properties and uses different study scales. That complicates reconciling and using the collected hydrologic and geologic data in a consistent manner (Soulsby et al., 2008; Lin, 2003).

Geologists and geomorphologists have noted close relationships between bedrock lithology and the structure of the overlying drainage networks (Carlston, 1963). Visual analysis of drainage networks and the identification of patterns in these networks have been basic tools commonly used in photogeology to discriminate materials according to their lithology, which is an essential step in the development of geologic and geomorphological mapping at different scales (Soil Survey Division Staff, 1966). More recently, the influence of bedrock lithology on the configuration of flow systems has been reaffirmed (Gaudio et al., 2006; Bloomfield et al., 2011). Metrics to quantify this relationship are still being developed.

Drainage networks have complex shapes that require appropriate geometric measures to be quantified. The hierarchical classification of streams according to the branching structure of the drainage networks and the quantification of physical properties such as the length of the streams in the first half of the previous century demonstrated scaling properties of the drainage networks (Horton, 1932, 1945; Strahler, 1957). After the introduction of fractal geometry in the natural sciences (Mandelbrot, 1983), many researchers have investigated and confirmed the fractal and multifractal behavior of drainage networks (Rodríguez-Iturbe and Rinaldo, 1997; De Bartolo et al., 2000, 2004, 2006). Recent studies of the lithologic controls on the fractal and multifractal parameters of river networks (Gaudio et al., 2006; Dombradi et al., 2007) have analyzed areas, ranging from 100 to 10 000 km², considered as lithologically homogeneous. In other word, the differences in scaling properties of drainage networks are interpreted using a single dominant lithology in each of those networks.

Drainage networks are abundant that have developed in areas of heterogeneous lithology. The need and feasibility of analyzing the lithologic control on hydrologic

features in areas based on lithologic mapping have been recently suggested by Bloomfield et al. (2011).

The objective of this work was to evaluate the scaling properties of drainage networks within lithologic units and to research the relationships between scaling parameters of their geometric shapes. To exclude the effect of multiple in- and outflows in a lithologic unit, we focused this study on the first-order streams of the drainage networks.

1.2. STUDY AREA OVERVIEW

The study area (1 001 km²) is located in the western half of the Iberian Peninsula (Fig. 1.1), between the Spanish provinces of Zamora and Salamanca, and it corresponds to the specific wine production area of the Protected Designation of Origin “Arribes”.

Fig. 1.1. Overview of the study area showing the lithologic units studied, with an inset of a digital elevation model (DEM) of the study area.

The dendritic drainage networks of the study area belong to the Douro River basin and specifically to the left-side tributary system of the Douro River. The study area is bounded to the north and the west by the Douro River, to the southwest by the

Águeda River, and it is crossed east-southeast to west-northwest by other main rivers such as the Tormes, Huebra, and Uces rivers, sorted by decreasing magnitude.

The geology of the region was formed by the main orogenies that have sculpted the current configuration of the Iberian Peninsula. The plutonic rocks present in the area emerged during the Hercynian orogeny in the late Paleozoic era. The metamorphism caused by this movement transformed the oldest materials deposited during the Cambrian. Later, during the Mesozoic and the beginning of the Cenozoic, the area was part of an inland sea. During this period, the plutonic rocks (mainly granite) and the metamorphic rocks (ortogneisses, paragneisses, pelitic and psammitic metasediments, and others) were covered by sediments. Then, the Alpine orogeny balanced the Iberian Peninsula to the west and the inland sea was drained to the Atlantic Ocean through the cracks of the Hercynian basement. This process eroded the tertiary sediments, which remain only in a few places of the highest lands of the region.

From a geomorphological point of view, the study area is divided into two well-defined units, the peneplain, which includes the higher lands of the region, and the deep valleys of the rivers that go across it. The sharp contrast between the pronounced steepness of the valleys and the peneplain determines the climatic variations of the region.

According to the Köppen-Geiger climate classification (Köppen, 1918; Köppen and Geiger, 1928), the climatic conditions of the valleys are classified as Csa (mild humid climate with a wet winter and a dry and hot summer), while the climatic conditions of the peneplain are classified as Bsk (cold semiarid climate characterized by grasslands where the mean annual precipitation varies according to the mean annual temperature). The main difference between these two classes is the temperature regime, due to the protection of the valleys from the dominant winds coming from the Atlantic Ocean (Gómez-Miguel et al., 2011).

The tectonic stability and the low climatic variability of the region are essential preconditions for the effective study of the lithologic controls on the drainage network (Dombradi et al., 2007; Bloomfield et al., 2011).

The land use is also noteworthy. According to the National Geographic Information System of Agricultural Fields (SIGPAC), the area of the average field in

the studied zone is only 0.74 ha, and usually the borders between fields are stone walls built some centuries ago. These wall represent an efficient soil conservation practice, but they also condition the natural process of channel incision and hence the development of the drainage network.

1.3. MATERIALS AND METHODS

1.3.1. Data set

This study was performed using two sources of information: the lithologic information of the soil map of the region, scale 1/25 000 (Gómez-Miguel et al., 2011) and the drainage network, digitized from aerial photograms.

The lithologic information of the soil map shows that there are 257 lithologic unit, 176 of which belong to three source rock types: plutonic rocks (P), metamorphic rocks (M), and sedimentary materials (S). To carry out this study, 20 lithologic units with areas ranging from 10 to 50 km² were selected. Eleven of the 20 selected units correspond to the plutonic rocks present in the area and are called P1 to P11 from the largest to the smallest; eight units represent the metamorphic rocks (M1-M8); and only one is representative of the sedimentary materials (S).

The drainage network was obtained through photointerpretation by stereoscopic viewing of 267 aerial photograms, 23 by 23 cm, scale 1/18 000. We considered all evidence on the terrain of continuous or intermittent watercourses, and we have considered as first-order streams those streams that do not have tributaries. Once identified on the photograms, the information about the drainage network was translated by hand to a vector file using the available orthophotograms of the region with a resolution of 25 cm as spatial reference.

1.3.2. Box-Counting method

The method used for the estimation of the fractal dimension in this work was the box-counting method, which belongs to the family of fixed-size algorithms. This method represents one of the simplest methods of scaling analysis from a computational point of view and it has been widely used to obtain generalized fixed-size algorithms

successfully applied to the multifractal characterization of river networks (De Bartolo et al., 2000, 2004, 2006).

According to Rodríguez-Iturbe and Rinaldo (1997), to obtain the box-counting dimension the studied geometric object has to be covered with a regular grid of side r . Then the number $N(r)$ of grid boxes that contain some part of the object is counted. The r value is progressively reduced to obtain a series of smaller sizes and corresponding $N(r)$ numbers. As $r \rightarrow 0$, $\log N_i / \log(1/s_i)$ converges to a finite value defined as the box-counting dimension. In this expression, $N_i = N(r_i)$ and $s_i = r_i/r_1$, where r_1 is the first grid size considered for the box-counting dimension estimation. Figures 1.2 and 1.3 illustrate the procedure. The box-counting dimension corresponds to the slope gradient of the regression line shown in Fig. 1.2.

Fig. 1.2. Log-log plot of the number of boxes that intersect the studied feature (N_i) vs. the size of the intersected boxes (s_i) for the drainage system of the lithologic unit P5.

In this study case, the whole drainage network was totally covered by a square of 81 920 by 81 920 m centered on the central point of the extension of the layer (X_UTM:713583; Y_UTM:4570899; Coordinate system: European Datum 1950 29N). This square was divided into four similar boxes of 40 960 by 40 960 m. This step was repeated until the initial square had been divided into 16 777 216 boxes of 20 by 20 m. Due to the irregular shape of the lithologic units and the way in which the boxes of different sizes represent the shape of the lithologic unit (Fig. 1.3a), the box sizes

considered as representative for the fractal dimension estimation were 320, 160, 80, 40, and 20 m. According to the above nomenclature, $r_1 = 320$ m, $r_2 = 160$ m, $r_3 = 80$ m, $r_4 = 40$ m, and $r_5 = 20$ m (Fig.1.3).

The method used to estimate lacunarity was adapted from the gliding box method described by Borys (2009). Lacunarity was obtained by considering the number of empty boxes (20 by 20 m) within each box of 320 by 320 m.

Fig. 1.3. Box-counting method applied to the drainage network of the lithologic unit P5: (a) boxes of 320 by 320 m occupied by the drainage network ($s_1 = 320/320 = 1$); (b) boxes of 80 by 80 m ($s_3 = 80/320 = 1/4$); (c) boxes of 20 by 20 m ($s_5 = 20/320 = 1/16$); and (d) the original drainage network.

All confidence intervals shown in this work are at the 95% confidence level.

1.4. RESULTS

1.4.1. Quantitative framework of fluvial geomorphology

Eight variables describing the area, the drainage system, and the first-order streams of the 20 lithologic units are provided in Table 1.1.

Table 1.1. Quantitative description of the 20 lithologic units and their drainage systems.

Unit	Drainage system					First-order streams		
	Area	Length	Drainage density	Highest order	Tributary to a main river	Length	No. of streams	Avg. length
	<i>km²</i>	<i>m</i>	<i>km/km²</i>			<i>m</i>		<i>m</i>
P1	38.13	176,108	4.62	fourth	yes	101,974	471	216.5
P2	32.98	170,772	5.18	sixth	no	104,417	495	210.9
P3	25.63	76,424	2.98	fourth	no	47,006	147	319.8
P4	22.76	123,104	5.41	fifth	no	76,559	341	224.5
P5	18.56	100,383	5.41	fourth	no	55,024	267	206.1
P6	18.29	76,937	4.21	fourth	yes	46,247	212	218.1
P7	15.17	74,959	4.94	sixth	yes	42,466	193	220.0
P8	15.13	53,631	3.54	fifth	no	31,213	116	269.1
P9	13.51	58,502	4.33	fourth	yes	34,993	165	212.1
P10	12.80	38,251	2.99	third	no	22,822	67	340.6
P11	10.42	45,642	4.38	fourth	yes	26,542	132	201.1
M1	44.39	196,648	4.43	fifth	yes	107,620	449	239.7
M2	42.06	144,943	3.45	fifth	yes	90,422	302	299.4
M3	37.59	123,731	3.29	sixth	yes	71,082	242	293.7
M4	34.27	145,950	4.26	fourth	yes	91,522	383	239.0
M5	16.94	84,013	4.96	fourth	yes	47,752	249	191.8
M6	15.19	61,954	4.08	fifth	yes	35,494	172	206.4
M7	13.28	54,258	4.09	fourth	yes	33,669	145	232.2
M8	10.13	52,885	5.22	sixth	yes	31,961	174	183.7
S	10.77	26,939	2.50	fourth	no	17,935	99	181.2

The drainage density values refer to the whole lithologic unit. According to these values, there are no differences between plutonic and metamorphic units; the drainage density for the plutonic rocks is 4.36 ± 0.50 km/km² while the value for the metamorphic rocks is 4.22 ± 0.43 km/km². Similarly, the average lengths of the first-order streams are almost equal for the plutonic unit (239.9 ± 27.2 m) and the metamorphic units (235.7 ± 27.9 m). In both cases, for the drainage density and the average length of first-order streams, the values for sedimentary unit are lower. However, as there is only one sedimentary unit, we avoid any statistical comparisons because we have no evidence of its representativeness. The presence of main rivers

bounding or crossing the lithologic unit in all metamorphic units suggests some preference or easiness of water erosion of this kind of material compared with the plutonic rocks.

1.4.2. Fractal dimension of the drainage systems

According to the box-counting values reported in Table 1.2, the fractal dimension of the drainage systems, D , of the plutonic units is 1.139 ± 0.027 , while the D of the metamorphic units is 1.108 ± 0.016 . D value for the sedimentary units is <1 .

Table 1.2. Box-counting results including fractal dimension (D) and reference density (a) for the drainage systems of the 20 lithologic units.

Unit	No. of grid boxes occupied by the drainage system with different box sizes expressed in m														
	D	a	R^2	40,960	20,480	10,240	5,120	2,560	1,280	640	320	160	80	40	20
P1	1.1671	2.6746	0.9938	1	2	3	7	18	44	132	418	1163	2640	5427	11051
P2	1.1979	2.6269	0.9926	4	4	4	5	13	34	115	369	1077	2484	5241	10627
P3	1.0710	2.4057	0.9986	1	2	2	4	9	26	83	241	559	1172	2359	4802
P4	1.2143	2.4685	0.9921	1	2	2	4	11	23	79	255	756	1786	3760	7691
P5	1.1582	2.4298	0.9964	1	2	2	4	11	29	84	246	636	1456	3048	6221
P6	1.1415	2.3446	0.9943	1	1	1	3	9	22	62	197	533	1180	2400	4851
P7	1.1700	2.2990	0.9933	1	1	1	3	7	22	58	175	495	1113	2305	4678
P8	1.0831	2.2374	0.9984	1	1	1	4	9	23	58	163	385	802	1663	3347
P9	1.1302	2.2336	0.9957	1	1	2	4	7	19	52	155	405	885	1822	3672
P10	1.0755	2.1008	0.9988	1	2	3	5	7	15	44	120	277	579	1191	2406
P11	1.1218	2.1322	0.9952	1	1	2	3	6	16	40	122	321	696	1410	2841
M1	1.1474	2.7328	0.9942	1	4	4	7	16	48	147	480	1319	2892	5942	12060
M2	1.0969	2.6642	0.9968	1	2	3	6	15	42	127	424	1059	2245	4544	9163
M3	1.0962	2.5951	0.9976	1	2	3	7	15	41	124	366	892	1899	3883	7835
M4	1.1349	2.6296	0.9942	1	1	2	6	15	41	120	379	1030	2238	4572	9188
M5	1.1213	2.4026	0.9952	2	2	3	7	11	28	71	228	592	1309	2627	5274
M6	1.0762	2.3209	0.9962	1	1	2	5	10	25	65	191	482	981	1960	3947
M7	1.0835	2.2538	0.9980	1	1	2	5	10	21	60	168	400	845	1731	3452
M8	1.1038	2.2236	0.9957	2	2	2	2	6	20	54	152	386	840	1673	3348
S	0.9983	2.0397	0.9972	1	1	2	4	8	18	42	102	236	455	857	1703

The a value reported in Tables 1.2 and 1.3 represents the intersection of the regression line with the ordinate axis (Fig. 1.2). The high values of the coefficient of determination (R^2), > 0.9920 in all the estimations, suggest scale invariance of the studied features at the study scale. It is worth noting that, for example, for the lithologic unit P5, the R^2 of the fit with box sizes of 5 120, 2 560, 1 280, 640, and 320 m is higher (0.9996) than the R^2 of the fit (0.9964) with box sizes considered in the study (320, 160,

80, 40, and 20 m). Although the R^2 is higher with those pixel sizes, the scale invariance suggested by this value of R^2 is attributable to the shape of the lithologic unit and not to the drainage system because the smallest size is 320 m and, according to Fig. 1.3, this box size does not reflect drainage information.

1.4.3. Fractal dimension of the first-order streams

Results in Table 1.3 show that the fractal dimension of the first-order streams, D_1 , is slightly higher in the plutonic rock units (1.003 ± 0.022) than in the metamorphic rock units (0.976 ± 0.015). Here again the values are below or very close to 1, but the R^2 values suggest clear scaling properties in all the sets of first-order streams.

Table 1.3. Box-counting results including fractal dimension (D_1) and reference density (a_1) for the first-order streams of the drainage systems of the 20 lithologic units.

Unit	No. of grid boxes occupied by the drainage system with different box sizes expressed in m														
	D_1	a_1	R^2	40,960	20,480	10,240	5,120	2,560	1,280	640	320	160	80	40	20
P1	1.1671	2.6746	0.9938	1	2	3	7	18	44	125	381	935	1859	3494	6749
P2	1.0558	2.6014	0.9927	3	3	3	4	12	33	113	353	921	1888	3599	6933
P3	0.9566	2.3353	0.9996	1	2	2	4	9	25	81	211	433	824	1563	3058
P4	1.0780	2.4390	0.9920	1	2	2	4	11	23	77	241	646	1352	2595	5042
P5	1.0133	2.3642	0.9971	1	1	2	4	11	28	79	215	494	1002	1905	3669
P6	0.9989	2.3032	0.9968	1	1	1	3	9	22	62	186	432	843	1595	3086
P7	1.0189	2.2401	0.9948	1	1	1	3	7	20	54	157	387	760	1445	2776
P8	0.9586	2.1624	0.9989	1	1	1	4	8	22	54	139	296	561	1060	2036
P9	0.9959	2.1818	0.9965	1	1	2	4	7	18	49	140	328	633	1204	2305
P10	0.9610	2.0199	0.9995	1	2	3	5	7	15	40	102	212	395	767	1499
P11	0.9814	2.0772	0.9955	1	1	2	3	6	15	38	109	259	488	912	1743
M1	0.9892	2.6736	0.9969	1	4	4	7	16	48	144	437	1012	1931	3672	7071
M2	0.9818	2.5994	0.9987	1	2	3	6	15	41	124	379	826	1587	3043	5933
M3	0.9559	2.5217	0.9995	1	2	3	6	14	39	120	324	670	1248	2410	4692
M4	1.0191	2.5724	0.9955	1	1	2	6	15	41	115	340	827	1625	3105	6000
M5	0.9627	2.3605	0.9960	2	2	3	7	11	28	69	211	484	919	1678	3187
M6	0.9470	2.2376	0.9986	1	1	2	5	9	22	60	165	354	648	1220	2367
M7	0.9819	2.1806	0.9986	1	1	2	5	10	21	58	144	317	600	1171	2252
M8	0.9668	2.1844	0.9969	2	2	2	2	5	19	52	142	320	615	1127	2158
S	0.8901	2.0037	0.9978	1	1	2	4	8	18	41	96	200	351	621	1191

Plotting the values of D_1 vs. D , we find two different results depending on the bedrock lithology (Fig. 1.4). The result obtained for the eight metamorphic rock units does not show any trend, while the plot of the plutonic rock units reflects a positive linear relationship. This clear trend suggests some regularity in the eroding process of

the granitic rocks, probably due to their internal configuration. This regularity does not appear in the metamorphic units, whose materials are affected by the directions of the metamorphic process.

Fig. 1.4. Plots of the fractal dimension of the first-order streams (D_1) vs. the fractal dimension of the drainage systems (D).

1.4.4. Intercepts

The parameters a for the drainage systems and a_1 for the first-order streams shown in Tables 1.2 and 1.3 have been typically related to the reference density or the number of the counted boxes of the largest size. The very strong correlation between parameters a and a_1 in the two studied scaling laws reflects a similarity in scaling of both the drainage networks and the set of their first-order streams (Fig. 1.5). This relationship seems not to be affected by lithology and probably reflects the effects of other environmental factors.

Fig. 1.5. Plots of the reference density parameter of the drainage system (a) vs. the reference density parameter of the first-order streams (a_1).

Plotting the values resulting from the box-counting method for the two studied scaling laws shows a weak dependence of parameter a on the fractal dimension D (Fig. 1.6). This supports the assumption that the fractal dimension and the reference density of the two features are controlled by different environmental factors. However, the lithologic units with similar source rock type, which are represented in the same color, appear to be grouped (Fig. 1.6).

Fig. 1.6. Plots of the fractal dimension (D and D_1) vs. the reference density parameter (a and a_1) for the two studied scaling laws, drainage system on the left and first-order streams on the right, for the plutonic (P), metamorphic (M), and sedimentary (S) lithologic units.

1.4.5. Lacunarity

Lacunarity was calculated for both the drainage network of each lithologic unit (Λ) and the set of its first-order streams (Λ_1). The Λ of the plutonic units is 1.00465 ± 0.00065 , while the Λ of the metamorphic units is 1.00408 ± 0.00025 . In the case of Λ_1 , the value for the plutonic rock units is 1.00203 ± 0.00023 and the value for the metamorphic rock units is 1.00189 ± 0.00014 . Like the values of D and D_1 , the values of Λ and Λ_1 for the sedimentary unit are the lowest of the studied units (1.00230 and 1.00121, respectively). The linear relationship between Λ and Λ_1 , with $R^2 = 0.834$, suggests a similarity in the two scaling laws (Fig. 1.7).

Fig. 1.7. Plots of the lacunarity of the drainage system (Λ) vs. the lacunarity of the first-order streams (Λ_1) for the plutonic units (P), metamorphic units (M), and sedimentary units (S).

The results reflect that Λ and Λ_1 increase as D and D_1 increase (Fig. 1.8). This finding supports the idea that the fractal dimension and the lacunarity are controlled by the same environmental factors. The linear relationship between Λ and D ($R^2 = 0.777$) is stronger than the relationship between Λ_1 and D_1 ($R^2 = 0.633$).

Fig. 1.8. Plots of the fractal dimension (D and D_1) vs. the lacunarity (Λ and Λ_1) for the two studied scaling laws, drainage system on the left and first-order streams on the right, for the plutonic (P), metamorphic (M), and sedimentary (S) lithologic units.

As in Fig. 1.6, the lithologic units with similar rock type are shown grouped in Fig. 1.8.

1.5. DISCUSSION

1.5.1. Suitability of the assumed scaling model

The method and the scale range used for the estimation of the fractal dimension seem to be appropriate, resulting in R^2 values that suggest the scale invariance of the studied hydrologic features at the study scale.

The box-counting method is known to be very sensitive to border effects, and it is not able to determine the correct dimension for the negative moment order of the multifractal spectrum (De Bartolo et al., 2000; Gaudio et al., 2004). However, the procedure followed here, with an initial box size (320 m) significantly smaller than the study unit, suggests a suitable sensitivity to the study objective. If larger box sizes were used, we would estimate the scaling properties of the shape of the lithologic unit and not of the drainage network.

The manual editing of the drainage network could introduce some identification and digitization errors, but using this data set we are free of other methodological errors related to the channel network extraction from digital elevation models (Helmlinger et al., 1993).

1.5.2. Properties of fluvial geomorphology

The values obtained for the plutonic and the metamorphic units are very similar. These results support the fact that in Gaudio et al. (2006), the metamorphic and the plutonic rocks were grouped as the same source rock type. The reported values of drainage density for the plutonic and metamorphic rocks are lower than those presented by Gaudio et al. (2006) for the plutonic and metamorphic areas of the Calabrian region (4.93-6.24 km/km²). These differences could be based on the topographic differences between this part of Italy and our study area of Spain. Also, it is possible that the stone walls present in the region, which divide the landscape everywhere, play a role as a soil conservation practice that affects the drainage density.

1.5.3. Fractal scaling parameters

The presented values of the fractal dimension of the drainage networks are clearly lower than those previously reported by Gaudio et al. (2006) and Dombradi et al. (2007) for areas having similar source rock types to the lithologic units studied here. however, the values of D for the drainage networks are close to 1.1, which together with 1.5 and 1.7 are the "more likely" fractal dimension values of river networks described by Claps and Oliveto (1996).

The case of the values of D_1 is significant in that almost all the lithologic units present values <1 . The interpretation of the results of D and D_1 is linked to the range of box sizes used in the estimation of the fractal dimension. Values of D_1 ranging from 0 to 1 represent intermediate situations between the existence of many streams shorter than 20 m and separated >320 m ($D_1=0$) and the presence of several first-order streams crossing the lithologic unit from side to side and separated from each other by >320 m ($D_1=1$). Values of $D_1>1$ are related to the highest drainage densities. The only lithologic unit (S) with a D value <1 shows many scattered in- and outflows resulting in a drainage system without a clear branching structure.

Other scaling parameters considered in this work are the reference density parameter and lacunarity. The reference density appears to be very close for the two features -drainage networks and lithology- evaluated from different sources of data. Because the scaling dimension are different, the densities diverge as the size of the boxes grows. The notion of lacunarity, which was introduced by Mandelbrot (1983), makes it possible to distinguish between geometric objects having similar fractal dimensions. Our results show that Λ increases as D increases in our study case. This positive relationship suggests that both parameters could be controlled by the same environmental factors and contradicts the assumption that Λ and D are inversely related.

1.6. CONCLUSIONS

The lithologic control on the geometry of drainage systems was investigated using techniques of fractal analysis within 20 delimited areas with homogeneous bedrock lithology. The tectonic stability and the low climatic variability of the region allowed effective study of the lithologic control on the drainage network.

The very simple tool of monofractal analysis used, the box-counting dimension, has allowed identification of the scaling properties of the drainage system of irregular lithologic units and also the scaling properties of the sets of first-order streams, which geometrically represent scattered set of lines.

The relationship between the fractal dimension of both hydrologic features shows a different behavior between the metamorphic and the plutonic units that was not appreciable from the results of the traditional quantitative measures of fluvial geomorphology.

The lacunarity and the reference density parameter complement the fractal dimension to describe patterns of spatial dispersion in hydrologic features such as the sets of first-order streams.

This work indicates that using the available information in soil survey databases may be very advantageous in interdisciplinary studies.

CHAPTER 2.

IDENTIFICATION OF BEDROCK LITHOLOGY USING FRACTAL DIMENSIONS OF DRAINAGE NETWORKS EXTRACTED FROM MEDIUM RESOLUTION LIDAR DIGITAL TERRAIN MODELS.

ABSTRACT

Geologists know that drainage networks can exhibit different drainage patterns depending on the hydrogeological properties of the underlying materials. Geographic Information System (GIS) technologies and the increasing availability and resolution of digital elevation data have greatly facilitated the delineation, quantification, and study of drainage networks. This study investigates the possibility of inferring geological information of the underlying material from fractal and linear parameters describing drainage networks automatically extracted from 5-m-resolution LiDAR digital terrain model (DTM) data. According to the lithological information (scale 1/25 000), the study area is comprised of 30 homogeneous bedrock lithologies, the lithological map units (LMUs). These are mostly igneous and metamorphic rocks, but also include some sedimentary rocks. A statistical classification model of the LMUs by rock type has been proposed based on both the fractal dimension and drainage density of the overlying drainage networks. The classification model has been built using 16 LMUs, and it has correctly classified 13 of the 14 LMUs used for its validation. Results for the study area show that LMUs, with areas ranging from 177.83 ± 0.01 to 3.16 ± 0.01 km², can be successfully classified by rock type using the fractal dimension and the drainage density of the drainage networks derived from medium resolution LiDAR DTM data with different flow support areas. These results imply that the information included in a 5-m-resolution LiDAR DTM and the appropriate techniques employed to manage it are the only inputs requires to identify the underlying geological materials.

2.1. INTRODUCTION

Drainage networks indicating paths of overland flow concentration are the geomorphological result of climate, tectonics, geology and time (Lifton and Chase, 1992). Drainage networks are present everywhere, even in remote places such as the largest of Saturn's moons, Titan, where the climatic condition are hugely different to those currently found on Earth (Cartwright et al. 2011). Furthermore, the evidence of their existence are still present today in places like Mars where the tectonic activity and the overland fluid disappeared long time ago (Hynek and Phillips, 2003).

For many decades of the past century the study of a drainage network entailed the accomplishment of a huge and thorough delineation work, Nowadays, the evolution of Geographic Information Systems (GIS), the increasing resolution and availability of digital elevation data, the development of specific algorithms (O'Callaghan and Mark, 1984; Tarboton, 1997), and the increasing computer power available in personal computers have simplified the delineation of drainage networks and facilitated their use in hydrological studies. However, the proper delineation of drainage networks is still a complex problem due to the scale dependence of digital terrain models (DTMs) and drainage networks (Helmlinger et al., 1993). The answer to the question where do channels begin (Montgomery and Dietrich, 1988, 1992) is still being investigated (Tesfa et al., 2011; Schwanghart et al., 2013).

Geologists know that drainage networks show different drainage patterns depending on the geological properties of the underlying materials. This knowledge represents one of the fundamental aspects of photo-geology, which is the use of aerial photographs to interpret the geology of a region and to compile geological maps from them. In fact, the first step of geological and soil mapping, after the proper preparation of the aerial photographs, is the delineation of drainage networks at the finer scales allowed by the aerial photographs (Allum, 1966).

Almost 50 years ago, Howard (1967) proposed a qualitative classification of drainage patterns that is reproduced nowadays in most geology textbooks. The different classes of drainage patterns are dendritic, parallel, pinnate, trellis, rectangular, radial, and annular. Each of these classes is related to different landforms, rocks, or slope

steepness in a qualitative way. Fortunately, some authors have since decided to quantify the complexity involved in the architecture of these natural structures. The first works quantitatively ordering and describing the drainage networks (Horton, 1932, 1945; Strahler, 1957) revealed important relationships between their elements and were used to establish a series of ratios known as Hortonian laws that still today are commonly used in hydrological studies. These works provided the first evidence of the scaling properties of drainage networks. Research on these scaling properties led hydrologists to the recognition of the fractal and multifractal nature of drainage networks (Rodríguez-Iturbe and Rinaldo, 1997; De Bartolo et al., 2000, 2004, 2006; Gaudio et al., 2004; Ariza-Villaverde et al., 2013) that is changing the way drainage networks are investigated.

The question follows that if drainage networks are fractals, and the drainage patterns are controlled by geology, can fractal measures of drainage networks be used to help answer the question of what is the underlying lithology?

Some author have explored the lithologic control on drainage networks concluding that fractal measures are related to the lithologic characteristics of the source rocks (Gaudio et al., 2006), and are more influenced by tectonic uplift than by lithology (Dombradi et al., 2007). However, the study units in these works were entire basins (Dombradi et al., 2007) or large areas of 100s of km² (Gaudio et al., 2006), where more than one homogeneous bedrock lithology would be expected. The use of study units defined by semi-detailed scale lithological maps has been recently suggested (Bloomfield et al., 2011; Cámara et al., 2013) and could enlighten the problem and provide further conclusive results.

The objective of this study was to investigate if the fractal dimension of the drainage networks automatically extracted from medium resolution DTM data could quantitatively identify geological characteristics of the underlying materials. One aspect that the authors want to emphasize is that the drainage networks derived with different flow support areas from LiDAR DTMs were used to capture the terrain irregularity resulting from erosion and fragmentation processes caused by current or past climatic conditions on different geological materials, instead of to solve the problem of perfect delineation of the current drainage streams.

2.2. MATERIALS AND METHODS

2.2.1. Study area

The study area is located in Northwest Spain (Fig. 2.1), and it corresponds to the wine growing region called ‘Arribes’. This area is entirely placed on the Duero River Basin. The Duero River is the third longest river in the Iberian Peninsula. It flows East to West crossing Spain and Portugal to the Atlantic Ocean.

Fig. 2.1. Overview of the study area showing the 30 lithological units under study.

The Arribes landscape is characterized by deep canyons formed by the Douro River and the main rivers of its left-side tributary system, i.e. the Tormes, Uces, Huebra, and Águeda Rivers. These canyons are carved into the surrounding peneplain, which

was formed by igneous and metamorphic rocks from the Hercynian orogeny. Sedimentary materials, that filled the Douro Basin during the Cenozoic Era, surface the highest zones of the peneplain.

The Arribes climate shows a xeric soil moisture regime, which is the typical moisture regime in areas of Mediterranean climate (Soil Survey Staff, 2014), and a mesic soil temperature regime with a mean annual soil temperature between 8 and 15°C. The annual rainfall is close to 600 mm all across the region (Gómez-Miguel et al., 2011). The main mesoclimatic differences inside the region are determined by the landscape. Thus, the lower parts of the canyons, which are protected against the dominant Atlantic winds, show higher mean annual temperatures than those recorded on the peneplain. According to the Köppen-Geiger climate classification scheme (Köppen, 1918; Köppen and Geiger, 1928), the climate of the canyons is classified as Csa (temperate climate with dry and hot summer) while the climate of the peneplain is classified as Bsk (arid climate steppe cold).

2.2.2. Data set

Three sources of information of the study area were used for this paper: the soil map, scale 1/25,000, the 5-m-resolution DTM, and the drainage network obtained by photogrammetric methods.

The lithological information contained in the soil map units has been used to define the lithological map. It is worth noting that during the creation of the soil map, at a scale of 1/25,000, the boundaries between different lithologies were delineated by refining the National Geologic Map of Spain, at a scale of 1/50,000, using photographic interpretation of aerial photographs (23 x 23 cm), scale 1/18,000.

The soil map units with the same lithological information were dissolved using ArcGIS 10.1 to generate the Lithological Map Units (LMUs). The lithological map contains 257 LMUs of 13 lithological groups. Table 2.1 shows a brief description of the lithological groups included in the lithological map, and also the geological map unit number and the sheet number of the National Geological Map of Spain, scale 1/50,000 (MAGNA50) matching the lithological group. An exhaustive description of the geological map units can be consulted online at the website of the Instituto Geológico y Minero de España (<http://info.igme.es/cartografia/magna50.asp>).

Table 2.1. Lithological groups included in the lithological map of the region.

Code	Geological time		Lithological group		MAGNA50	
	Era	Period	Type of rock	Brief description	Sheet n°	Unit
T1	Cenozoic	Miocene	Sedimentary	Conglomerates with heterometric pebbles	449	25
S1	Cenozoic	Paleogene	Sedimentary	Lutites and silts	423	16
A1	Paleozoic	-	Filonian	Quartz dikes and pegmatites	449	1
I1	Paleozoic	Ordovician	Igneous	Ortoneisses metagranitic, and granite	423	3
I2	Paleozoic	Devonian	Igneous	Granite: medium grained, two-mica with abundant quartz dikes	423	11
I3	Paleozoic	Devonian	Igneous	Granite: medium to coarse grained, two-mica, porphyritic	475	3
I4	Paleozoic	Devonian	Igneous	Granite: coarse grained, two-mica, not porphyritic	475	10
I5	Paleozoic	Devonian	Igneous	Granite: coarse to very coarse grained, biotitic, porphyritic	449	11
I6	Paleozoic	Devonian	Igneous	Granite: fine to medium grained, two-mica, leucocratic	449	17
I7	Paleozoic	Devonian	Igneous	Inhomogeneous granitoids, migmatites, microporphyritic	423	7
M1	Paleozoic	Precambrian	Metamorphic	Pelitic paragneiss interbedded with quartzite	422	16
M2	Paleozoic	Cambrian	Metamorphic	Pelitic and psammitic metasediments interbedded with quartzite	449	19
M3	Paleozoic	Ordovician	Metamorphic	Alternating level of shales and quartzitic shales	449	23

Thirty LMUs of the lithological map were chosen to carry out the study (Table 2.2). The initial criterion for the choice was the selection of the 30 biggest LMUs. In this selection there was only one LMU of sedimentary material. Therefore, the smallest LMU of the initial group of 30 was replaced by the sedimentary LMU S1_02. Nine different lithological groups, which cover 97.3 % of the total area of the studied region, are represented within these 30 LMUs. The nine lithological groups belong to the three types of rock mentioned above: igneous, metamorphic, and sedimentary rocks.

Table 2.2. Lithological groups in the study area, and in the 30 selected LMUs.

Code	Study area			30 LMUs selected		
	Area		No. LMUs	Area		No. LMUs
	km ²	%	Count	km ²	%	Count
T1	4.50	0.5	14	-	-	0
S1	15.20	1.5	6	13.93	1.6	2
A1	1.07	0.1	23	-	-	0
I1	35.58	3.6	19	23.41	2.7	2
I2	100.82	10.2	18	95.03	11.1	6
I3	197.18	20.0	16	183.22	21.4	2
I4	88.07	8.9	18	83.45	9.8	3
I5	77.24	7.8	38	56.42	6.6	2
I6	148.24	15.0	34	127.72	14.9	6
I7	17.21	1.7	26	-	-	0
M1	132.47	13.4	27	111.79	13.1	4
M2	166.55	16.9	16	159.88	18.7	3
M3	3.90	0.4	2	-	-	0
	988.04		257	854.85		30

Table 2.4, which is placed in the "Results" section, shows a quantitative geomorphological description of the 30 LMUs.

The DTM used in this study is a 5-m-resolution DTM generated from LiDAR data with a density of 0.5 point/m². The altimetric accuracy of the medium resolution DTM has a root mean square deviation equal to or less than 0.5 meters. The DTM data source was the Instituto Geográfico Nacional de España© (IGN). These data are freely available under registration on the "Download Centre" of the IGN's website (<http://www.ign.es>). According to Vaze et al., (2010), medium resolution LiDAR DTMs are quality data to capture the nature and complexity of drainage networks, even more than high-resolution LiDAR DTMs, with grid sizes equal to or less than 1 m², which generate a greater noise effect (Zandbergen, 2010).

The drainage network of the studied area was delineated in previous works by the authors (Gómez-Miguel et al., 2011). The drainage network is a vector file obtained by stereoscopic view of the aerial photographs cited above, which was delineated over the 25-cm-resolution orthophotos of the region, considering all the evidence of continuous or intermittent watercourses on the terrain. No comparable similar scale hydrological data are available. Figure 2.2 shows a visual comparison between the finer scale of the available hydrological data and the digitized drainage network used in this study.

Fig. 2.2. Drainage networks included in the National Topographic Map of Spain (A), scale 1/25,000, and the digitized drainage network obtained by photogrammetric methods (B).

2.2.3. Method of drainage network extraction

The cartographic operations were carried out with the Hydrology Toolbox included in the Spatial Analyst extension of the software ArcGIS 10.1, which was developed by the University of Texas (Maidment, 2002). The method of extraction of drainage networks included in ArcGIS is based on the maximum gradient method, also known as the D8 algorithm, which was proposed by O'Callaghan and Mark (1984).

In this study, six drainage networks were generated from the LiDAR-DTMs by applying six different values of the flow accumulation threshold (FAT). The six FAT values used correspond to flow support areas of 2500, 5000, 10000, 20000, 30000, and 40000 m² (Fig. 2.3).

Fig. 2.3. Details of the digitized drainage network of the LMU M2_01 (A), details of the drainage networks automatically extracted with the different flow support areas; 2500 m² (B), 5000 m² (C), 10000 m² (D), 20000 m² (E), 30000 m² (F), 40000 m² (G), and details of the 5-m-resolution LiDAR DTM (H).

The drainage network obtained by photogrammetric restitution was compared in the 30 LMUs with the automatically extracted drainage network aiming to explore which FAT values generates the drainage network most similar to the delineated one.

2.2.4. Geomorphological approach to the LMUs

The medium resolution LiDAR DTM was also used to calculate a topographic index of the LMUs. The calculated index was the hypsometric integral (HI) which was introduced by Strahler (1952). This index has been traditionally used in the analysis of river basins as a classic measure of erosional stage. In this study, the HI was not applied to defined watersheds, but to LMUs.

The method selected for the estimation of the HI was the elevation-relief ratio, which was proposed by Pike and Wilson (1971). Following this method, the HI is expressed as

$$HI = \frac{E_{mean} - E_{min}}{E_{max} - E_{min}} \quad (2.1)$$

where E_{mean} is the weighted mean value of the 5-m-DTM pixel values belonging to the LMU, E_{max} is the maximum elevation value of the LMU, and E_{min} is the minimum elevation value. The appropriateness of this method has been recently reaffirmed (Singh et al., 2008).

Some basic characteristics of the LMUs such as the area, the perimeter, and the area-perimeter ratio were also quantified.

A classic measure in hydrology, the drainage density, was calculated on the LMUs for the seven drainage networks under investigation. A theoretical FAT value of the digitized drainage network (FAT_{DD}) was calculated for each LMU by relating the drainage density of the digitized drainage network to the decreasing evolution with the FAT increments of the drainage density of the automatically extracted drainage networks.

2.2.5. Fractal analysis: Box counting method

The fractal dimension of the drainage networks was estimated applying a fixed-size algorithm known as the box counting method, which was introduced by Russel et al. (1980). The box counting method has been widely used in fractal analysis since fractals were brought onto the scientific scene by Mandelbrot (1983).

As is described by Rodríguez-Iturbe and Rinaldo (1997), the box counting method consists of a two dimensional analysis of an object. The object is covered by a regular grid of side r . Then, the number of grid boxes containing the object is counted, obtaining the value $N(r)$. The r value is halved repeatedly and the series of N_i values is obtained by counting the occupied boxes. Taking a reference box size (r_1), the size factor (s) is calculated as $s_i = r_i/r_1$. As r decreases, the following relation is obtained:

$$\frac{\log N_i}{\log \left(\frac{1}{s_i} \right)} \quad (2.2)$$

which converges to a finite value defined as the box counting dimension.

The entire study area has been covered by a square of 81.92 km $\times$ 81.92 km. This square has been sequentially subdivided until it formed a grid of 15.625 cm. The reference box size has been established at 320 m because bigger box sizes capture the scaling properties of the contour and shape of the LMU and don not provide further hydrological information. Figures 2.4 and 2.5 illustrate the box counting method and its results.

Fig. 2.4. Box counting method applied to the drainage network of the LMU I2_04 extracted with the FAT value 20,000 m². The boxes of size 320 m (A), 80 m (B), 20 m (C), and 5 m (D) occupied by the drainage network.

The minimum box size considered for the estimation of the fractal box counting dimension was set by the scale of the LiDAR-DTM, which means a box size of 5 m. The box counting dimension was estimated using the scale range between $r_1 = 320$ m and $r_7 = 5$ m for the seven drainage networks in the 30 LMUs. The coefficients of determination (R^2) for these estimations were higher than 0.990 in all of the 210 cases investigated.

Fig. 2.5. Log-log plot of the number of boxes that intersect the drainage network (N_i) versus the size factor of the intersect boxes ($1/s_i$). The numbers reflect the scaling behavior, for pixel sizes from 81.92 km to 15.625 cm, of the drainage network of the LMU I5_02 extracted with the FAT value 10000 m².

The box counting dimension of the digitized drainage network was used within each LMU to estimate the theoretical FAT value (FAT_{FD}) that would generate a drainage network with the same value of the box counting dimension as the digitized drainage network. Figure 2.6 illustrates the procedure employed to obtain the FAT_{FD} .

Fig. 2.6. Method applied to calculate the flow accumulation threshold value that theoretically would generate a drainage network with the same fractal dimension as the digitized drainage network.

2.2.6. Statistical analysis

The 21 quantitative variables describing the LMUs, initially considered to perform the statistical analyses, are shown in Table 2.3.

Table 2.3. Quantitative variables describing the LMUs used to perform the statistical analysis.

Abbrev.	Description
HI	Hypsometric Integral
E mean	Weighted mean elevation of the LMU expressed in 'meters above sea level'
Area	Area of the Lithological Map Units expressed in km ²
Perimeter	Perimeter of the Lithological Map Units expressed in m
Ratio A/P	Ratio Area-Perimeter of the Lithological Map Unit expressed in m
DD _{2,500}	Drainage density of the drainage network obtained with FAT = 2,500 m ²
DD _{5,000}	Drainage density of the drainage network obtained with FAT = 5,000 m ²
DD _{10,000}	Drainage density of the drainage network obtained with FAT = 10,000 m ²
DD _{20,000}	Drainage density of the drainage network obtained with FAT = 20,000 m ²
DD _{30,000}	Drainage density of the drainage network obtained with FAT = 30,000 m ²
DD _{40,000}	Drainage density of the drainage network obtained with FAT = 40,000 m ²
DD _{DIGITIZED}	Drainage density of the digitized drainage network
FAT _{DD}	Theoretical FAT obtained for the digitized drainage network based on DD _{DIGITIZED}
FD _{2,500}	Fractal dimension of the drainage network obtained with FAT = 2,500 m ²
FD _{5,000}	Fractal dimension of the drainage network obtained with FAT = 5,000 m ²
FD _{10,000}	Fractal dimension of the drainage network obtained with FAT = 10,000 m ²
FD _{20,000}	Fractal dimension of the drainage network obtained with FAT = 20,000 m ²
FD _{30,000}	Fractal dimension of the drainage network obtained with FAT = 30,000 m ²
FD _{40,000}	Fractal dimension of the drainage network obtained with FAT = 40,000 m ²
FD _{DIGITIZED}	Fractal dimension of the digitized drainage network
FAT _{FD}	Theoretical FAT obtained for the digitized drainage network based on FD _{DIGITIZED}

An ANOVA test was performed to investigate the variance behavior of each variable, grouping the LMUs by type of rock and by lithological group. Unfortunately, each lithological group was represented by a number of LMUs too small, so that the results obtained for these groups were not statistically significant.

A statistical classification model of the LMUs by type of rock was proposed based on the discriminant analysis of the linear and fractal parameters that describe the drainage networks.

Discriminant analysis is multivariate analysis of variance which is used to determine which continuous variables discriminate between different naturally occurring groups. In discriminant analysis, the independent variables are the predictor and the dependent variables are the groups (Poulsen and French, 2004).

The 16 LMUs used to generate the classification model were S1_01, I1_01, I2_01, I2_03, I2_05, I3_01, I4_01, I4_03, I5_01, I6_01, I6_03, I6_05, M1_01, M1_03, M2_01, and M2_03. The remaining 14 LMUs under investigation were used to validate the classification model within the study area. All of the confidence intervals are shown at the 95 % confidence level.

2.3. RESULTS

2.3.1. Morphological properties of the lithological map units

A quantitative geomorphological approach to the LMUs is shown in Table 2.4. The results reflect the morphological heterogeneity of the studied LMUs. These 30 LMUs together covered 86.5 % of the wine growing region. The area of the LMUs ranged from the 177.83 km² of the biggest LMU (I3_01) to the 3.15 km² of the smallest LMU (S1_02). The area/perimeter ratio was significantly related to the logarithm of the area, with a coefficient of determination (R^2) equal to 0.694.

The variability of the HI values in our study agrees with Hurtrez and Lucazeau (1999) who concluded that relief characteristics at small and meso-scales are independent of the type of rock. However, the geological information managed by Hurtrez was scale 1/1000000, and it is logical to assume that this information scale was too coarse for small scale relief studies.

The HI values were higher than 0.500, except for the LMU I3_02 unit. It is significant that this unit gave the highest E_{mean} value, which means that this LMU was placed on the peneplain. Although the HI has been calculated in areas of homogeneous lithology instead of in defined watersheds, the HI values could be interpreted as an indication of the erosional stage of the LMU. Thus, in this study, the lower HI values are present in the LMUs located in the highest or the lowest zones of the region. This is reasonable because the peneplain, which is by definition an erosional surface, is placed in the higher parts of the region, while the lower parts of the canyons are actually the most eroded ones.

Table 2.4. Quantitative variables describing the LMUs used to perform the statistical analysis.

LMU	Hypsometric	Elevations in DTM data				Area	Perimeter	Ratio A/P
	Integral	E_{min}	E_{max}	E_{mean}	Std. Dev.			
	(HI)	<i>masl</i>	<i>masl</i>	<i>masl</i>		<i>km²</i>	<i>m</i>	<i>m</i>
S1_01	0.621	684	809	762	19.1	10.778	42,671	252.6
S1_02	0.593	727	763	748	6.8	3.155	28,000	112.7
M1_01	0.703	625	789	728	28.8	42.057	45,653	921.2
M1_02	0.782	325	713	522	89.4	37.594	62,732	599.3
M1_03	0.684	521	785	727	27.8	16.944	82,385	205.7
M1_04	0.647	229	696	560	108.4	15.195	60,058	253.0
M2_01	0.613	415	768	674	60.3	81.212	90,623	896.2
M2_02	0.631	545	743	706	26.2	44.393	67,369	658.9
M2_03	0.703	725	786	764	10.1	34.275	67,024	511.4
I1_01	0.629	187	690	537	137.9	13.279	59,576	222.9
I1_02	0.508	512	806	745	31.2	10.134	53,241	190.3
I2_01	0.780	594	677	635	17.8	32.984	58,462	564.2
I2_02	0.709	383	786	694	71.0	22.758	30,500	746.2
I2_03	0.734	373	683	606	38.2	13.507	35,033	385.5
I2_04	0.812	750	803	781	10.6	10.422	25,306	411.8
I2_05	0.639	187	730	586	118.5	7.934	31,974	248.1
I2_06	0.696	188	765	674	81.4	7.423	20,304	365.6
I3_01	0.791	594	804	746	20.5	177.831	163,445	1,088.0
I3_02	0.489	741	820	784	15.7	5.385	15,607	345.0
I4_01	0.773	122	630	414	126.2	52.089	97,180	536.0
I4_02	0.753	667	779	728	25.4	18.565	67,233	276.1
I4_03	0.578	698	768	738	11.8	12.797	22,721	563.2
I5_01	0.734	324	753	632	94.4	38.127	70,706	539.2
I5_02	0.842	516	817	728	50.4	18.291	43,748	418.1
I6_01	0.721	429	747	678	55.8	57.474	77,833	738.4
I6_02	0.544	323	750	615	92.9	25.627	33,896	756.1
I6_03	0.575	382	707	592	76.4	15.168	37,720	402.1
I6_04	0.548	122	662	453	130.6	15.127	42,215	358.3
I6_05	0.570	187	723	525	122.8	8.426	18,989	443.8
I6_06	0.718	324	753	632	94.4	5.901	28,670	205.8

2.3.2. Drainage density

This traditional measure in hydrology has been calculated for all of the LMUs, for the digitized drainage network, and also for the six drainage networks automatically extracted with different FAT values. The results of these calculations are shown in Table 2.5.

As expected, the drainage density of the drainage networks decreased as the FAT values used to generate them increased. If more area is needed to begin channelization, channels are shorter, and the drainage density is lower.

Table 2.5. Drainage densities of the drainage networks obtained with different FAT values (DD_{FAT}).

LMU	DD_{2500}	DD_{5000}	DD_{10000}	DD_{20000}	DD_{30000}	DD_{40000}	$DD_{DIGITIZED}$	FAT_{DD}
S1_01	12.19	6.37	3.91	2.63	2.20	1.88	3.12	16,202
S1_02	8.92	4.02	2.00	0.95	0.68	0.54	1.65	13,332
M1_01	11.64	7.18	4.79	3.63	3.10	2.76	4.03	16,519
M1_02	18.84	10.71	6.34	4.17	3.30	2.86	3.80	24,287
M1_03	17.97	9.90	6.01	4.23	3.63	3.18	5.36	13,647
M1_04	15.40	8.32	5.15	3.64	3.15	2.82	4.85	11,977
M2_01	13.52	7.63	4.94	3.57	3.06	2.73	5.17	9,568
M2_02	16.94	9.56	5.91	4.21	3.59	3.24	4.60	17,708
M2_03	16.82	9.09	5.53	3.88	3.27	2.94	4.70	15,009
I1_01	19.49	11.08	6.78	4.54	3.56	3.13	4.49	20,563
I1_02	15.66	9.07	5.88	4.20	3.53	3.20	6.02	9,790
I2_01	17.69	10.37	6.57	4.47	3.63	3.13	5.17	16,642
I2_02	17.11	9.74	6.21	4.33	3.57	3.11	5.41	14,271
I2_03	15.40	8.84	5.88	4.05	3.23	2.79	4.44	17,854
I2_04	16.36	9.47	6.14	4.04	3.24	2.81	4.49	17,872
I2_05	20.56	12.66	7.28	4.97	3.74	3.12	3.83	33,420
I2_06	18.50	10.42	6.42	4.27	3.39	2.87	4.51	18,877
I3_01	15.79	9.94	6.44	4.33	3.50	3.01	3.56	29,233
I3_02	13.18	8.47	5.71	4.08	3.39	2.88	3.85	23,338
I4_01	17.16	10.10	6.43	4.41	3.62	3.18	4.35	20,760
I4_02	15.37	10.10	6.89	5.04	4.25	3.86	5.41	18,007
I4_03	18.18	11.35	7.19	4.70	3.62	3.02	2.99	*40,442
I5_01	17.58	10.19	6.37	4.32	3.48	2.99	4.87	17,305
I5_02	17.47	10.27	6.47	4.22	3.27	2.74	4.47	18,866
I6_01	18.51	11.12	7.00	4.69	3.75	3.19	3.90	28,442
I6_02	18.11	11.34	7.29	4.73	3.67	3.07	2.98	*41,485
I6_03	19.91	11.28	6.69	4.43	3.65	3.22	5.23	16,474
I6_04	20.53	11.64	6.88	4.32	3.31	2.79	3.55	27,625
I6_05	19.80	11.83	7.43	4.71	3.60	2.95	3.07	38,133
I6_06	21.13	11.66	6.53	4.22	3.54	3.08	3.97	23,579

* values out of the tested range of FAT values

The decrease of the drainage density with increasing FAT values matches a potential curve. The coefficient of determination for this fit were higher than 0.970 for all the 30 LMUs. The theoretical FAT values (FAT_{DD}) ranged from 9568 m² to 38133 m². Two of the 30 LMUs produced $DD_{DIGITIZED}$ values lower than $DD_{40\,000}$ values.

2.3.3. Fractal box counting dimension

The fractal box counting dimension of the drainage networks was estimated using the box size range between 320 and 5 m (Table 2.6). The coefficients of determination (R^2) of these estimations were higher than 0.990 in all the 210 cases studied.

Table 2.6. Fractal dimensions of the drainage networks obtained with different FAT values (FD_{FAT}).

LMU	FD_{2500}	FD_{5000}	FD_{10000}	FD_{20000}	FD_{30000}	FD_{40000}	$FD_{DIGITIZED}$	FAT_{FD}
S1_01	1,2523	1,1151	1,0381	0,9905	0,9750	0,9684	1.0279	12,141
S1_02	1,1300	1,0088	0,9113	0,8525	0,8160	0,7954	0.8787	15,551
M1_01	1,2885	1,1786	1,0961	1,0498	1,0306	1,0150	1.0810	13,263
M1_02	1,3998	1,2629	1,1496	1,0794	1,0496	1,0357	1.0713	22,709
M1_03	1,3403	1,1996	1,0998	1,0491	1,0254	1,0164	1.0816	13,593
M1_04	1,3056	1,1608	1,0676	1,0225	1,0020	0,9924	1.0680	9,977
M2_01	1,3292	1,1947	1,1075	1,0541	1,0390	1,0283	1.1193	9,325
M2_02	1,3849	1,2450	1,1417	1,0833	1,0597	1,0459	1.1005	17,057
M2_03	1,3658	1,2178	1,1119	1,0486	1,0289	1,0234	1.0907	13,347
I1_01	1,3557	1,2263	1,1266	1,0688	1,0440	1,0316	1.0603	23,426
I1_02	1,2904	1,1638	1,0830	1,0385	1,0170	1,0125	1.0748	11,848
I2_01	1,3774	1,2495	1,1564	1,0883	1,0628	1,0470	1.1171	15,775
I2_02	1,3920	1,2559	1,1561	1,0975	1,0744	1,0614	1.1280	14,806
I2_03	1,3290	1,1987	1,1140	1,0486	1,0253	1,0177	1.0685	16,952
I2_04	1,3429	1,2165	1,1262	1,0586	1,0248	1,0059	1.0752	17,551
I2_05	1,3762	1,2694	1,1719	1,1099	1,0606	1,0348	1.0313	*41,375
I2_06	1,3784	1,2423	1,1386	1,0737	1,0496	1,0308	1.0873	17,910
I3_01	1,3719	1,2642	1,1720	1,1033	1,0746	1,0618	1.0785	28,642
I3_02	1,2770	1,1946	1,1119	1,0539	1,0419	1,0198	1.0585	19,210
I4_01	1,3710	1,2425	1,1460	1,0794	1,0536	1,0437	1.0809	19,771
I4_02	1,3047	1,2106	1,1350	1,0833	1,0627	1,0497	1.1014	16,497
I4_03	1,3848	1,2748	1,1835	1,1020	1,0717	1,0447	1.0446	*40,021
I5_01	1,3845	1,2537	1,1562	1,0867	1,0578	1,0400	1.1082	16,901
I5_02	1,3705	1,2475	1,1493	1,0697	1,0428	1,0272	1.0888	17,602
I6_01	1,3988	1,2778	1,1812	1,1165	1,0874	1,0723	1.0755	37,939
I6_02	1,3992	1,2907	1,1983	1,1244	1,0948	1,0809	1.0452	*65,802
I6_03	1,4093	1,2715	1,1578	1,0904	1,0611	1,0541	1.1089	17,261
I6_04	1,3971	1,2678	1,1636	1,0869	1,0556	1,0431	1.0584	29,103
I6_05	1,3929	1,2714	1,1706	1,1057	1,0691	1,0486	1.0426	*42,922
I6_06	1,3630	1,2186	1,1025	1,0380	1,0133	1,0042	1.0154	29,146

* values out of the tested range of FAT values

As was described for the drainage density results, the decrease of the fractal dimension with increasing FAT values matches a potential curve. The quality of the fitting was slightly lower but the R^2 values were still higher than 0.930 for all the 30 LMUs.

The theoretical FAT values (FAT_{FD}) ranged from 9325 to 37939 m^2 , and four of the 30 LMUs produced $FD_{DIGITIZED}$ values lower than the FD_{40000} values.

2.3.4. LMUs results grouped by type of rock

The results for the LMUs of the 21 variables described in Table 2.2 have been grouped by type of rock (Table 2.7). The results for the sedimentary LMUs have to be taken into account carefully because the study population is very small.

Table 2.7. Results of the variables calculated for the LMUs grouped by rock type.

	Type of rock			
	Sedimentary	Metamorphic	Igneous	ALL
Code	S	M	I	-
Count	2	7	21	30
Variable				
HI	0.607 ± 0.028 a	0.680 ± 0.042 a	0.673 ± 0.046 a	0.671 ± 0.034
Area (km^2)	6.97 ± 7.47 a	38.81 ± 16.28 a	27.11 ± 16.02 a	28.50 ± 12.01
Ratio A/P	182.7 ± 137.1 a	578.0 ± 208.4 b	466.9 ± 95.3 ab	473.9 ± 87.2
DD_{2500}	10.56 ± 3.20 a	15.88 ± 1.89 b	17.79 ± 0.87 b	16.86 ± 1.01
DD_{5000}	5.19 ± 2.30 a	8.91 ± 0.94 b	10.52 ± 0.46 c	9.79 ± 0.65
DD_{10000}	2.95 ± 1.88 a	5.52 ± 0.44 b	6.62 ± 0.23 c	6.12 ± 0.41
DD_{20000}	1.79 ± 1.64 a	3.91 ± 0.22 b	4.43 ± 0.12 c	4.13 ± 0.27
DD_{30000}	1.44 ± 1.48 a	3.30 ± 0.17 b	3.55 ± 0.10 b	3.35 ± 0.22
DD_{40000}	1.21 ± 1.31 a	2.93 ± 0.15 b	3.05 ± 0.10 b	2.90 ± 0.19
$DD_{DIGITIZED}$	2.38 ± 1.44 a	4.64 ± 0.42 b	4.30 ± 0.37 b	4.25 ± 0.34
FAT_{DD}	14767 ± 2813 ab	15531 ± 3506 a	23475 ± 3775 b	21041 ± 3054
FD_{2500}	1.191 ± 0.120 a	1.345 ± 0.030 b	1.365 ± 0.016 b	1.349 ± 0.021
FD_{5000}	1.062 ± 0.104 a	1.208 ± 0.027 b	1.243 ± 0.014 c	1.223 ± 0.020
FD_{10000}	0.975 ± 0.124 a	1.111 ± 0.021 b	1.148 ± 0.012 c	1.127 ± 0.018
FD_{20000}	0.921 ± 0.135 a	1.055 ± 0.015 b	1.082 ± 0.011 b	1.065 ± 0.018
FD_{30000}	0.896 ± 0.156 a	1.034 ± 0.014 b	1.055 ± 0.009 b	1.039 ± 0.018
FD_{40000}	0.882 ± 0.170 a	1.022 ± 0.013 b	1.040 ± 0.009 b	1.025 ± 0.018
$FD_{DIGITIZED}$	0.953 ± 0.146 a	1.087 ± 0.013 b	1.074 ± 0.012 b	1.069 ± 0.016
FAT_{FD}	13846 ± 3342 ab	14182 ± 3370 a	25736 ± 5683 b	22247 ± 4464

Different letters in a row indicate significant differences ($P < 0.05$). LSD test

According to the ANOVA test, 5 of the 21 variables showed significant differences in their means by type of rock at the 95 % confidence level. These variables were DD_{5000} , DD_{10000} , DD_{20000} , FD_{5000} , and FD_{10000} . Figure 2.7 graphically shows the results of the LMUs grouped by rock type, showing the mean values and the confidence intervals of the drainage density and the fractal dimension results of the groups of metamorphic and igneous LMUs. The sedimentary LMUs have been removed from the

graph because, due to the small number and the variability of the sedimentary LMUs, the confidence intervals for this group were physically inconsistent.

Fig. 2.7. Fractal dimension and drainage density of the drainage networks automatically extracted with different FAT values. Data are grouped by type of rock: Igneous rock (*red*) and Metamorphic rocks (*blue*). The points represent the mean value of the group and the lines define the 95 % confidence intervals.

The HI values by Hurtrez and Lucazeau (1999) for granite (0.45) and schist (0.29) in the Hérault basin are lower than those obtained in our study.

2.3.5. Classification model of LMUs in different types of rock

The statistical classification model of the LMUs by type of rock proposed in this study was determined by discriminant factorial analysis. The classification model was built using the 16 LMUs of sedimentary, metamorphic, and igneous rock indicated in the Sect. 2.2. Beginning with the 21 variables describing the LMUs, the discriminant analysis determined the 8 variables selected for the statistical classification model. These variables were $DD_{5\,000}$, $DD_{10\,000}$, $DD_{20\,000}$, $DD_{40\,000}$, $FD_{5\,000}$, $FD_{10\,000}$, $FD_{20\,000}$, and

FD_{40 000}. This classification model was validated using the remaining 14 LMUs. Thirteen of these 14 LMUs were successfully classified by type of rock. The visual analysis of the aerial orthophotos of the wrongly classified LMU I6_06 revealed that within the third smallest LMU (5.39 km²), and probably affecting the results, there is a town, called Villarino de los Aires with about a thousand inhabitants, and an hydroelectric power station with an installed capacity of 810 MW. It is noteworthy that only fractal and linear parameters describing the drainage networks automatically extracted from 5-m-resolution LiDAR DTMs were needed to classify the LMUs by their type of rock in the study area.

The coefficients of the classification functions for each type of rock are provided in Table 2.8.

Table 2.8. Coefficients of the classification functions for each type of rock.

	Type of rock		
	Sedimentary S	Igneous I	Metamorphic M
FD ₅₀₀₀	6116.76	12075.50	12084.30
FD ₁₀₀₀₀	-7708.09	-13332.50	-13610.90
FD ₂₀₀₀₀	424.09	370.42	937.56
FD ₄₀₀₀₀	7909.55	7351.37	7027.38
DD ₅₀₀₀	64.29	-98.50	-82.06
DD ₁₀₀₀₀	-752.44	-607.53	-656.47
DD ₂₀₀₀₀	1550.62	1841.16	1862.30
DD ₄₀₀₀₀	-951.60	-955.07	-970.83
K value	-3325.38	-3998.12	-3869.93

According to this table, the classification function for the sedimentary rock (S) is

$$\begin{aligned}
 S \text{ value} \equiv & 6116.76 \cdot FD_{5000} - 7708.09 \cdot FD_{10000} + 424.089 \cdot FD_{20\ 000} + \\
 & + 7909.55 \cdot FD_{40\ 000} + 64.2871 \cdot DD_{5000} - 752.441 \cdot DD_{10\ 000} + \\
 & + 1550.62 \cdot DD_{20\ 000} - 951.595 \cdot DD_{40\ 000} - 3325.38
 \end{aligned}
 \tag{2.3}$$

In order to classify a new LMU, the three classification function must be calculated, and the type of rock assigned to the LMU would be the type of rock of the classification function obtaining the highest value of the three classification functions.

The representation of the 30 LMUs on the two first discriminant functions (Fig. 2.8) shows considerable dispersion of the LMUs belonging to the same class, which was more evident for the sedimentary LMUs. This means that this classification model is not extremely solid, and also that it needs more replications on different materials and probably substantial modifications to be able to be applied over large scales. However, the existence of this classification model itself represents evidence of the suitability of our approach.

Fig. 2.8. Representation of the LMUs on the two first discriminant functions. The circled LMUs were used to develop the classification model, and the rest of LMUs were used to validate it. The igneous LMU I6_06 within the triangle was the only LMU that was wrongly classified as metamorphic rock.

The results strongly suggest that the information included in a 5-m-resolution LiDAR DTM and the appropriate techniques to manage it could be the only inputs required to identify the underlying type of rock.

2.4. DISCUSSION

The complexity and the irregularity of the topographical relief are caused by the landscape forming factors, but the different effects or expressions of these causes are determined by the underlying geological materials and their responses to erosion and fragmentation processes.

In Howard's work on drainage patterns (Howard, 1967), the author mentioned that in any small area, where all other factors are held constant, drainage texture may provide information on underlying materials and indirectly on structure.

In our analysis, drainage networks automatically extracted from the DTM were not considered properly defined hydrological features. Instead, they were considered fractal structures capturing the topographic relief roughness produced by the landscape forming factors on different geological materials. Topographic expression, fault situation, and drainage patterns are considered intrinsic characteristics of the lithological material that photo-geologic interpretation techniques can qualitatively identify (Allum, 1966), and that this study aims to quantify.

This perspective make it possible to investigate the underlying geological material, independently of the hydrologic factor such as groundwater inputs or the current seasonality of precipitation, even in remote places where hydrologic factor have not acted for a long time. The results of the statistical classification model proposed in this study seem to validate our approach and the applied techniques.

However, the proposed classification method only resulted in a coarse classification of the geological materials which was only validate for the study area. The small number of LMUs included in the study precludes statistical analysis of the lithological groups. More replications are needed on each lithological group and on different lithological material to enable a finer classification by lithological group instead of the proposed classification by type of rock.

The inclusion in the analysis of other elements strongly linked to the bedrock lithology, such as the particle-size distribution of the soils developed on it, is currently being investigated (Cámara et al., 2015) and could make it possible to perform a finer discrimination between lithological material. These kind of studies, addressing the heterogeneity and process complexity of watershed hydrology at all scales, are being

vigorously pursued to advance watershed and hydrogeological science (McDonnell et al., 2007; Lin, 2003).

The consolidation of robust statistical classification models to identify the underlying lithological material from DTM could represent the basis to implement tools for the automatic delineation of different lithological materials.

2.5. CONCLUSIONS

This paper has investigated the role of drainage networks extracted automatically from medium resolution DTMs in identifying the underlying lithological materials. The investigation was carried out by applying fractal analysis techniques to the drainage networks of 30 areas of homogeneous bedrock lithology located in Northwest Spain. These areas of homogeneous bedrock lithology are lithological map units (LMUs) defined by the available lithological data, at a scale 1/25,000. The types of rock included in these 30 areas were mostly igneous and metamorphic, but there were also some sedimentary rock present.

Six different flow accumulation threshold (FAT) values were used for the extraction of the drainage networks from the 5-m-resolution LiDAR DTM, and the six resulting drainage networks were compared with the drainage network obtained using photogrammetric methods.

The decreasing magnitudes of the fractal dimension and drainage density of the automatically extracted drainage networks with increasing FAT values matched potential curves for all of the LMUs. The coefficients of determination of the fits of all these curves were higher than 0.970 for the drainage density values and higher than 0.930 for the fractal dimension values.

A statistical classification model of the LMUs by type of rock has been proposed based on both fractal dimension and drainage density of the drainage networks.

The classification model was built using 16 LMUs of sedimentary, metamorphic, and igneous rocks. This model correctly classified 13 of the 14 LMUs used for its validation. The applicability of this model was not tested outside of the study area.

More replications of this procedure on different regions with different geological materials are needed to generalize our findings, but the results in the study area show that LMUs, with areas ranging from 177.83 to 3.16 km², can be successfully classified by type of rock, using the fractal dimension and the drainage density of the drainage networks derived from medium resolution LiDAR DTM with different flow support areas.

The results suggest that the information included in a 5-m-resolution LiDAR DTM and the appropriate techniques to manage it could be the only inputs required to identify the underlying geological material.

CHAPTER 3.

QUANTIFYING THE RELATIONSHIP BETWEEN DRAINAGE NETWORKS AT HILLSLOPE SCALE AND PARTICLE SIZE DISTRIBUTION AT PEDON SCALE

ABSTRACT

Nowadays, translating information about hydrologic and soil properties and processes across scales has emerged as a major theme in soil science and hydrology, and suitable theories for upscaling or downscaling hydrologic and soil information are being looking forward. The recognition of low-order catchments as self-organized systems suggests the existence of a great amount of links at different scales between their elements. The objective of this work was to research in areas of homogeneous bedrock material, the relationship between the hierarchical structure of the drainage networks at hillslope scale and the heterogeneity of the particle-size distribution at pedon scale. One of the most innovative elements in this work is the choice of the parameters to quantify the organization level of the studied features. The fractal dimension has been selected to measure the hierarchical structure of the drainage networks, while the Balanced Entropy Index (BEI) has been the chosen parameter to quantify the heterogeneity of the particle-size distribution from textural data. These parameters have made it possible to establish quantifiable relationships between two features attached to different steps in the scale range. Results suggest that the bedrock lithology of the landscape constrains the architecture of the drainage networks developed on it and the particle soil distribution resulting in the fragmentation processes.

3.1. INTRODUCTION

Drainage networks represent how water moves through the Earth's surface, and their structures are controlled by environmental factors such as climate, geology, and vegetation (Lifton and Chase, 1992; Tucker and Bras, 1998). The study of the drainage networks has implications in fields as diverse as ecology (Power and Dietrich, 2002; Bertuzzo et al., 2007), civil engineering (Youssef et al., 2011), or planetary sciences (Black et al., 2012), and its characterization, inventory, and understanding will be essential for an integrated management of the water resources in future, and also, to evaluate potential changes to environmental resources caused by changes in the land use or climate.

The development of specific algorithms for the automatic extraction of drainage networks from Digital Elevation Models (DEMs) (O'Callaghan and Mark, 1984; Tarboton, 1997) and the increasing resolution and availability of DEMs (Glennie et al., 2013; Vaze et al., 2010) have improved and facilitated its study.

According to the erosion cycle, a drainage system can be considered an open system which is progressively losing potential energy and mass (Schumm and Lichty, 1965). This loss of energy and material does not occur in an anarchic way, but occurs in a self-organized manner (Rodríguez-Iturbe and Rinaldo, 1997), generating hierarchical structures as the natural drainage networks. The recognition of this hierarchical behavior and the hierarchical ordering of the streams which compose the drainage system in the second third of the 20th century allowed significant advances in hydrology and geomorphology fields (Horton, 1945; Strahler, 1954, 1957). A similar step forward in the hydrologic knowledge as represented by these works is now requested by hydrologists who, unable to generalize the findings of the current hydrological models to ungauged areas, are in the ongoing quest for physically realistic catchment-scale models, that include more appropriate representations of the heterogeneous hydrological processes (Clarck et al., 2011; McDonnell et al., 2007).

To consider low-order catchments as self-organized systems suggests that their elements must be linked across scales. Nowadays, translating information about hydrologic and soil properties and processes across scales has emerged as a major

theme in soil science and hydrology, and suitable theories for upscaling and downscaling hydrologic and soil information are being looked forward (Lin et al., 2006). Finding quantitative relationships between factors as soil texture and structure, hydromorphology, preferential flow and water movement is a crucial goal for hypopedology (Lin, 2003).

Nevertheless, several works have already explores the relationship between hydrological features as the drainage networks and the environmental factors of the landscape at different scales. Drainage density is a traditional measure characterizing drainage networks that has been employed in many of these works. Drainage density has been related to slope steepness (Kirby, 1987), local relief (Strahler, 1964), bedrock geology (Morisawa, 1985), bedrock erodibility (Tucker and Slingerland, 1997) and hydraulic conductivity of the underlying soil (Montgomery and Dietrich, 1992; Bloomfield et al., 2011). Literature shows that this last variable has been largely related to soil texture and various models have been developed to estimate hydraulic conductivity from textural data (Rawls et al., 1982; Saxton et al., 1986; Ayra et al., 1999; Saxton and Rawls, 2006).

Recently, the relationship between lithology and the hierarchical architecture of drainage networks has been shown, and quantified by means of fractal dimension (Cámara et al., 2013). On the other hand, fragmentation (Perfect, 1997) and the erosion processes of different types of rocks are expected to generate different soil textures. It suggests the possibility of finding quantitative relationship between both last factors. Even the finding of weak relationship for factors so remote in the scale range at which they are attached might deserve the study.

The view of a drainage basin as a self-organized structure may help in choosing what quantifiable features might be related. This is a key point under the methodological point of view that this work aims to emphasize. The fractal dimension of a drainage network is seen as a measure of the complexity or level of organization at the hillslope scale. In the same manner, the point now is to research how to measure the level of organization of soil texture at the pedon scale.

After that, the huge number of intermittent interactions along the scales makes it wise to expect that certain organization level has been created, and it might be related with the fractal dimension of the network. On the other hand the theory of complex

systems, and particularly the Prigogine theory on dissipative structures (Nicolis and Prigogine, 1977), affirms that the organization level, which is tied with the concept of “heterogeneity” or “entropic level”, may be measured by means of the Shannon’s entropy.

Shannon’s entropy (Shannon, 1948a,b) is an information-theoretical parameter that may be suitably interpreted as a measure of the complexity of a distribution. In fact, entropy has already been proposed in life sciences as a plausible measure of biodiversity (Margalef, 1958) in the sense of evenness or heterogeneity of the diversity of species in an ecosystem. The Balanced Entropy Index (BEI) was introduced by Martín et al. (2005a), and it provides an efficient way of evaluating particle-size distribution (PSD) heterogeneity from textural data.

The objective of this work was to research, in areas of homogeneous bedrock material, the relationship between the hierarchical structure of the drainage networks at hillslope scale and the surficial soil texture at pedon scale. The quantification of particle size heterogeneity is made by means of the BEI cited above.

3.2. MATERIALS AND METHODS

3.2.1. Data set

This study was carried out using two sources of information: the soil map of the region, scale 1/25 000 (Gómez-Miguel et al., 2011), and the medium resolution DEM. Soil texture included in the soil map cited above was determined by Bouyoucos method (Bouyoucos, 1962). DEM data come from the Instituto Geográfico Nacional de España® (IGN), and correspond to a 5 m-resolution DEM generated from LiDAR data with a density of 0.5 point/m². Altimetric accuracy of the DEM has a root mean square deviation equal to or less than 0.5 m. These DEM data are freely available under registration on the website of the IGN (www.ign.es).

3.2.2. Study area

Eight square areas (1280 m x 1280 m), located within the Spanish wine growing region called "Arribes", have been selected to accomplish this study. The choice of the study sites was based on two criteria; first the study site must be entirely located in

areas of homogeneous lithology according the lithological information included in the soil map 1/25,000, and secondly it should include analytical data of more than three surficial soil samples of the soil map database (Fig. 3.1).

Fig. 3.1. 3D representation (Z factor = 3) of the study site P3, showing the 5 m-resolution DEM, the drainage networks with their streams hierarchically ordered, and the location of the surficial soil samples.

The eight study sites are distributed on two different lithologies dated in the Pre-Cambrian period, four of them [P1, P2, P3, and P4] are located on plutonic rocks, specifically on granite two-mica medium-grained, and the other four [M1, M2, M3, and M4] are situated on metamorphic rocks, particularly on pelitic and psammitic metasediments. The location of the eight study sites are provided in Table 3.1.

Table 3.1. Coordinates of the centroid of the study sites. Coord. Syst. WGS84 UTM Zone 29.

	Study sites							
	M1	M2	M3	M4	P1	P2	P3	P4
Coordinates								
X UTM	699499	702420	692488	682807	732978	738752	741742	745138
Y UTM	4567003	4565032	4552425	4541370	4596071	4598618	4597113	4591706

The soil of the study sites are majorly entisols, and more specifically Xerorthent typic, dystic, or lithic. Associated with the drainage streams there have been described

Xerofluvent typic and mollic. Only two inceptisols have been considered in this work, a Dystroxerept typic within the study site M1 and Haploxerept typic within M2.

The main climatic differences in the study area are determined by a very pronounced altitudinal thermal gradient (Cámara et al., 2012). According to the Köppen-Geiger climate classification (Peel et al., 2007) the low lands of the region, that represent a system of deep valleys, are classified as Csa (Temperate climate with dry and hot summer) while the high lands in the peneplain are classified as Bsk (Arid climate, steppe cold). The distribution of the mesoclimatic zones within the region (Cámara et al., 2012) indicates that the study site P2 is located between both climate classes, P4 is situated majorly in the climate class Bsk and the other study sites are entirely located in the climate class Csa.

3.2.3. Method for drainage network extraction

The Hydrology Toolbox included in the software ArcGIS 10.1, which was developed by the University of Texas (Maidment, 2002), was used to obtain the drainage network from the 5-m LiDAR-DEM. The drainage network extracting method in ArcGIS is based on the maximum gradient method, also called D8 algorithm, which was proposed by O'Callaghan and Mark (1984).

A constant area of 20000 m² has been established as flow accumulation threshold value to initiate the channelization during the process of drainage networks extraction. It is noteworthy that all the drainage networks obtained for the study sites with this threshold area correspond to intermittent watercourses.

3.2.4. Brief geomorphological description

The medium resolution DEM has also been used to obtain geomorphological information and to calculate some topographic indices traditionally related to certain characteristics of the drainage networks as the drainage density. A brief analysis of elevations and slopes angles has been carried out for the study sites, as well as the calculation of the Hypsometric Integral (HI) (Strahler, 1952). The HI values have been calculated by generating the elevation histogram from the 5 m DEM and using the following expression (Eq. 3.1) where E_{mean} is the mean value of the distribution of DEM

pixels values of the study site, E_{min} is the lowest value, and E_{max} is the highest value (Mahmood and Gloaguen, 2011).

$$HI = \frac{E_{mean} - E_{min}}{E_{max} - E_{min}} \quad (3.1)$$

Additionally, two properties of the drainage networks of the study sites have been investigated: the drainage density and the highest Strahler's order of the network (Strahler, 1957).

3.2.5. Fractal analysis methods

Three fractal parameters have been estimated in this work; the fractal dimension (D) and the lacunarity (Λ) of the drainage networks and the BEI of the soil particle-size distribution.

The fractal dimension of the drainage networks has been estimated using a fixed-size algorithm, the box-counting method (Russel et al., 1980). The method has been applied as it was described by Rodríguez-Iturbe and Rinaldo (1997).

Fig. 3.2. Box-counting method applied to the drainage network of the study site M3. From left to right and up down, grid boxes containing the drainage network with box sizes of 320, 160, 80, 40, 20 m, and the original drainage network automatically generated from the 5-m-resolution DEM.

The drainage network is covered by a grid of side r . In this work, the initial grid is only one cell of side $r = 1280$ m that matches to the study site. The number of grid boxes containing the network $N(r)$ is counted. The value of r is halved repeatedly and, by counting the boxes crossed by the network, a series of N_i value is obtained (Fig. 3.2). Once a reference box size (r_1) is established, the size factor is calculated as $s_i = r_i/r_1$. As r decreases to a threshold value the following relation

$$\frac{\log N_i}{\log \left(\frac{1}{s_i} \right)} \quad (3.2)$$

converges to a finite value defined as box counting dimension. In this work, the reference box size was 320 m ($r_1 = 320$ m), and the other sizes considered for the estimation were $r_2 = 160$ m, $r_3 = 80$ m, $r_4 = 40$ m, and $r_5 = 20$ m (Fig. 3.3).

Fig. 3.3. Log-log plot of the number of boxes that intersect the drainage network (N_i) versus the size factor of the intersected boxes ($1/s_i$) for the drainage network of the study unit P4.

The lacunarity of the drainage networks was obtained according to the method described by Borys (2009). For lacunarity estimation, the histogram of empty grid boxes of side r within grid boxes of side R needs to be calculated ($R > r$). In this work, $R = 320$ m and $r = 20$ m, agreeing this last value with the smaller grid box size used in the fractal dimension estimation. Once the histogram is obtained, lacunarity is characterized by statistical moments, defining lacunarity as the ratio of two expectation values,

$$\Lambda = \frac{E[X^2]}{E[X]^2} \quad (3.3)$$

where X is the variable describing the number of empty grid boxes of size 20 m within the grid boxes of size 320 m.

The BEI introduced by Martín et al. (2005a) is given by the simple formula

$$BEI = \frac{\sum p_i \log p_i}{\sum p_i \log l_i} \quad (3.4)$$

where the numbers l_i are the lengths of the three basic size intervals ($l_1 = 0.001$, $l_2 = 0.024$, $l_3 = 0.975$) and p_i are the soil's clay-silt-sand fractions. The formula above can be easily computed from conventional textural data and thus provides an efficient and straightforward way of evaluating PSD heterogeneity from textural data. Additional analysis and studies are still to be performed to evaluate the BEI suitability in the estimation of variables related to PSDs as, for instance, the specific surface area which is critical for modeling geochemical processes in soils.

The BEI takes values between 0 and 1, and its value may be interpreted as follows: the bigger the value of BEI the more heterogeneous the soil's PSD and in turn the richer the soil's texture. Moreover, since BEI may take any value from 0 to 1, entropy dimension supplies a continuum of textural classes, which is capable of a finer discrimination of soil textures, when compared with standard classifications. A thorough interpretation of the above formula and its theoretical properties in terms of textural analysis is given by Martín et al. (2005a).

3.2.6. Multivariate analysis

Aiming to analyze the interactions between the studied soil fractal parameters and properties and the hydrogeological fractal parameters and properties a multivariate statistical analysis has been carried out. A total of 11 variables have been considered in the analysis; the average altitude of the study sites (Altitude average), the average slope angle of the study sites (Slope angle average), the HI of the study sites, the drainage density of the drainage network of the study sites (Drainage density), the Strahler's order of the drainage network of the study sites (Order), the fractal dimension of the drainage network of the study sites (D), the lacunarity of the drainage network of the study sites (Λ), the average value of the BEI of the set of soil samples within the study

site, the average clay content of the set of soil samples within the study site (Clay), the average silt content of the set of soil samples within the study site (Silt), and the average sand content of the set of soil samples within the study site (Sand).

The statistical analysis for each variable has been realized, as well as the analysis of correlations between variables, and the principal components analysis. All these operations have been carried out by using the software Statgraphics Centurion XVI.I.

All confidence intervals in this work are shown at the 95 % confidence level.

3.3. RESULTS

3.3.1. Quantitative geomorphological approach to the study sites

Five variables describing the topography and the drainage system of the study sites are provided in Table 3.2. For both lithologies (M and P), the widest slope angle range and the highest slope angle average appear in the study site with the widest altitude range, M4 and P3, respectively.

Table 3.2. Quantitative description of the topography and the drainage network of the study sites

Study site	Altitude		Slope angle		Hypsometric Integral	Drainage density	Highest Strahler's order
	Range	Average	Range	Average			
	<i>masl</i>	<i>masl</i>	%	%	(HI)	<i>km/km²</i>	
M1	531 - 693	650	0 - 63	12.3	0.7346	4.28	3
M2	586 - 692	662	0 - 57	11.1	0.7170	3.81	4
M3	573 - 653	616	0 - 39	7.5	0.5375	4.96	3
M4	389 - 569	498	0 - 168	21.9	0.6056	3.26	2
P1	741 - 773	758	0 - 18	2.9	0.5313	3.78	3
P2	708 - 792	762	0 - 33	6.8	0.6429	4.65	3
P3	661 - 773	735	0 - 153	8.6	0.6607	4.18	3
P4	755 - 796	773	0 - 31	3.2	0.4390	5.07	3

Average slope angle is higher in metamorphic rock units (13.2 ± 6.0) than in plutonic rock units (5.4 ± 2.7). The HI values reported for the metamorphic units (0.65 ± 0.09) are little higher than those reported for the granitic units (0.57 ± 0.10) but there are not significant differences. A weak positive relationship ($R^2 = 0.232$) appears between the average slope angle and the HI values. This relationship is not statistically significant but it suggest a trend. The relationship is stronger considering only the

plutonic rock units ($R^2 = 0.806$) while it almost disappears for the metamorphic rock units ($R^2 = 0.001$) due to the values obtained for the M4 unit. Extracting this unit of the analysis, the relationship between the average slope angle and the HI values for the metamorphic units is clear ($R^2 = 0.974$).

A negative linear relationship ($R^2 = 0.427$) is shown between the average slope angle and the drainage density. This relationship is also not statistically significant, but it increases with removing the unit P1 of the analysis ($R^2 = 0.821$). The values of drainage density for the metamorphic units (4.08 ± 0.71) are similar to the values obtained for the plutonic units (4.42 ± 0.55).

3.3.2. Box-counting results of the drainage networks analysis

Results of the fractal dimension (D) and the lacunarity (Λ) of the drainage networks of the study sites are shown in Table 3.3.

Table 3.3. Box counting results for the drainage network of the study sites

Study site	Fractal dimension	Coefficient of determination for D estimation	Lacunarity	Number of grid boxes occupied by the drainage network with different boxes sizes				
				320 m	160 m	80 m	40 m	20 m
	(D)	(R^2)	(Λ)					
M1	1.1897	0.9903	1.004402	14	43	96	195	406
M2	1.1368	0.9965	1.003632	15	39	85	176	363
M3	1.1927	0.9920	1.003995	16	49	105	222	469
M4	1.0913	0.9970	1.002282	15	38	76	158	323
P1	1.1459	0.9967	1.005060	14	35	81	168	339
P2	1.1824	0.9946	1.004379	16	45	102	209	447
P3	1.1602	0.9944	1.004064	15	43	89	188	400
P4	1.2250	0.9980	1.005942	15	40	93	209	458

The suitability of the method to estimate the D of the drainage networks is supported by the high values of the coefficient of determination (R^2) of the estimation, which are higher than 0.990 in all cases. The D of the drainage system of the metamorphic units (1.1526 ± 0.0473) is lower than D of the plutonic rock units (1.1784 ± 0.0338). This behavior was already observed in other locations of the same region in the work of Cámara et al. (2013). The lacunarity of the drainage system developed on metamorphic rocks (1.0036 ± 0.0009) is lower than Λ of the plutonic rock units (1.0049 ± 0.0008).

Figure 3.4. Plots of the lacunarity (Λ) vs. the fractal dimension (D) of the drainage networks of the study sites, showing the metamorphic lithologies (blue points) and the plutonic lithologies (red points).

Figure 3.4 shows the relationship between Λ and D for both lithologies. These positive relationships contradicts the assumption that lacunarity and fractal dimension are inversely related and suggest that both the parameters could be controlled by the same environmental factors. D is also closely related to the calculated drainage density. Considering all the study sites, both variables show a positive linear relationship with a coefficient of determination $R^2 = 0.901$. Differentiating by lithologies, the relationship is stronger in the granitic sites ($R^2 = 0.943$) than in the metamorphic sites ($R^2 = 0.867$).

3.3.3. BEI of the particle-size distribution

Results have shown that the BEI averages 0.496 ± 0.074 for the 27 soil samples collected on metamorphic lithologies and 0.543 ± 0.075 for the 18 soil samples of the plutonic lithologies. By aggregating the results of the entropy dimension of the soil samples by study sites (Table 3.4), it is observed that the plutonic lithologies have a more uniform behavior (0.543 ± 0.010) than the metamorphic lithologies (0.493 ± 0.056).

According to Martín et al. (2005a), the majority of the obtained BEI values correspond to the sandy loam class of the United States Department of Agriculture (USDA) soil texture triangle. One of the advantages described in the work cited above using the BEI is represented by the suitability of the quantitative index to affine the textural classification. Although BEI values from 0.4 to 0.6 are all located in the sandy

loam class, values between 0.5 and 0.6 are shown to have greater contents of sand than soil samples with BEI values ranging from 0.4 to 0.5. Attending to our results we can affirm that fragmentation processes on pelitic and psammitic metasediments generate finer surficial soil texture than same processes on granitic rocks.

Table 3.4. BEI for the particle-size distribution of the surficial soil samples of the study sites

Study site	No. of samples	Balanced entropy index	Sand	Silt	Clay
		(BEI)	%	%	%
M1	9	0.4738 ± 0.0268	58.0 ± 4.4	30.2 ± 4.5	11.8 ± 1.7
M2	7	0.5605 ± 0.0465	73.0 ± 7.5	17.8 ± 7.7	9.2 ± 2.5
M3	5	0.4254 ± 0.0422	49.4 ± 7.3	39.6 ± 5.4	11.0 ± 3.7
M4	6	0.5131 ± 0.0673	68.8 ± 6.8	16.3 ± 3.0	14.9 ± 6.5
P1	4	0.5559 ± 0.0447	73.8 ± 7.3	15.0 ± 5.6	11.3 ± 2.4
P2	5	0.5451 ± 0.0569	70.6 ± 7.9	17.8 ± 4.7	11.6 ± 4.2
P3	5	0.5341 ± 0.0138	67.0 ± 2.4	23.0 ± 2.4	10.1 ± 0.1
P4	4	0.5373 ± 0.1511	63.8 ± 22.4	26.3 ± 15.7	10.0 ± 6.9

3.3.4. Finding across scales

Relating the fractal dimension, that quantifies the hierarchical architecture of the drainage networks, to the BEI, that quantifies the heterogeneity of the soil PSD for the eight study sites, both parameters seem lineally independent ($R^2 = 0.075$). By differentiating the study sites using bedrock materials some relationships emerge (Fig. 3.5). A negative relationship between D and BEI appears in both different lithologies. This weak relationship is not statistically significant but from a physical standpoint this negative trend was expected.

Geomorphologists know that drainage networks developed on coarse textures show lower drainage densities than drainage networks developed on finer textures. As coarse textures present higher values of BEI than fine textures, and fractal dimension and drainage density are closely related, it was expected that in areas with homogeneous bedrock lithology the values of the BEI, estimated for surficial soil samples, are lower when D increases. This behavior is more pronounced in the metamorphic rocks sites, while sites of plutonic rocks show more stability in values of BEI against changes in D .

Fig. 3.5. Plots of the fractal dimension (D) and the lacunarity (Λ) of the drainage networks of the study sites versus the BEI of the particle-size distribution of the surficial soil samples of the study sites, showing the metamorphic lithologies (blue points) and the plutonic lithologies (red points).

Although the relationship is weak, the bedrock material emerges as a key environmental factor that constrains the architecture of the drainage networks and the particle soil distribution resulting in the fragmentation processes.

3.3.5. Principal component analysis

Multivariate analysis has been initially carried out with the 11 described in Sec. 2.6. Variable “Order” has been removed from this analysis due to its value of standardized kurtosis obtained in the monovariate analysis, which indicates that this variable has a distribution significantly deviated from normality. The correlation analysis shows that the following pairs of variables are significantly correlated: Altitude average and Slope average, Altitude average and Λ , Slope average and Λ , Drainage density and D , D and Λ , BEI and Silt, BEI and Sand, and Silt and Sand. Aiming not to overvalue their weights in the principal components analysis, correlated variables have been removed. Finally, only five variables have been used in the analysis: Slope average, HI, D , BEI and Clay.

First and second principal components contain the 74.6% of data variability. The weight of the variables in the principal components shows that first principal component is mainly defined by three variables (Slope average, D and Clay), while second

principal component is mainly defined by the variable BEI. The proximity of the study sites with similar bedrock material in Fig. 3.6 suggests that explored soil and hydrological fractal parameters and properties, which describe the organization level of the system, could be the basis of statistical models to quantitatively classify bedrock materials or even to correct lithological maps.

Fig. 3.6. Representation of the study sites on the first and second principal components.

3.4. DISCUSSION

According to Clayton and Shamoon (1998) who studied the resistance of rocks to erosion for the relative relief of Britain, the Pre-Cambrian metasediments are more resistant to erosion than the Pre-Cambrian granites, and our results seem to reaffirm that finding in our study area. Higher values of average slope angle and HI, which in this work are shown in metamorphic units, are related in literature to harder bedrock materials (Mahmood and Gloaguen, 2011; Montgomery, 2001). Although granite seems to be more resistant to erosion than metamorphic rocks, except quartzite, the presence of biotite and the coarse grain in studied granites facilitate the erosion processes. Results of drainage network analysis agree with Strahler (1957), who reported similar values of drainage density for both plutonic and metamorphic lithologies.

The values of fractal dimension obtained in this work, ranging from 1.09 to 1.23, are lower than the values obtained by other authors (Gaudio et al., 2006; Dombradi et al., 2007). However, according to Claps and Olivetto (1996), the more expected values of fractal dimension of river networks are those values close to 1.1, 1.5, and 1.7. These

significant differences between our results and those reported in literature could be explained due to different methodologies to estimate the fractal dimension and different study scales. For us, the box sizes range employed in this work (320 to 20 m) is physically well chosen due to the nature of the drainage networks under investigation. According to Fig. 3.2, the use of box sizes bigger than 320 m would consider drainage network as a continuous plane and fractal dimension would tend to value 1.

The positive relationship between fractal dimension and lacunarity in drainage networks developed in homogeneous lithologies was recently affirmed (Cámara et al., 2013). Our present results reaffirm that finding.

The use of the BEI is probably the most innovative element of this work. One of the major advantages of the BEI is that it permits to discriminate between soil textures classified in the same textural class. The values of BEI obtained correspond to the same textural class in the USDA system, sandy loam, but by means of the BEI it has been possible to distinguish two groups inside this class, and each one of the studied bedrock lithologies is placed in a different group.

The aggregation of the individual data corresponding to the particle size distribution has being performed by the average value. Probably, further research considering some properties of the cartographic units of the soil map, as the area represented by each soil map unit within the study site, could establish more and clearer connections between the parameters which quantify the complexity of the system at different spatial scales. As well, the inclusion in the analysis of the heterogeneity represented by the distribution of soil horizons along the soil profile could enrich the results.

Similar analysis on different bedrock lithologies in other regions would help to address the suitability of the proposed methodology at global scale.

3.5. CONCLUSION

The quantitative relationship between the hierarchical structure of the drainage networks at hillslope scale and the surficial soil texture at pedon scale has been

investigated by means of fractal measures in 8 study sites (1.64 km²) distributed within areas of homogeneous bedrock lithology.

The automatic extraction of the drainage networks from medium resolution DEM has provided a starting point with quality enough to manifest environmental relationship at different scales, and suitable for the work objectives.

The fractal dimension (D) and the lacunarity (Λ) were the variables used to quantify the hierarchical structure of the drainage networks. The particle size heterogeneity was quantified using the BEI, introduced by Martín et al. (2005a). These three variables have demonstrated their capability to characterize and to quantify the complexity involved in natural system at different scales.

Although additional studies are still to be performed, the potential uses of BEI in Earth sciences are promising. This index is easily computable from textural data irrespective of the textural classification system and it provides a continuous textural parameterization that permits to numerically compare soil textures.

The fractal dimension of the drainage network shows a negative relationship with the BEI of the surficial soil samples. Thus, at least in both analyzed lithologies, finer textures are expected in drainage networks with higher values of fractal dimension.

Results suggest that the bedrock lithology which underlay the landscape constrains the architecture of the drainage networks developed on it and the particle soil distribution results of the fragmentation processes which affect it. Results of the multivariate analysis shows that the fractal dimension of the drainage network and the BEI of the particle-size distribution could be useful parameters to quantitatively classify bedrock materials.

CHAPTER 4.

LITHOLOGIC CONTROL ON SOIL TEXTURE HETEROGENEITY

ABSTRACT

Parent material is a soil forming factor which, specially in temperate climates, influences soil hydraulic properties. As direct measurements of the soil hydraulic properties are laborious, time-consuming and expensive, this work explores the influence of geological material on soil hydraulic properties using the Balanced Entropy Index (BEI) as a particle size distribution descriptor which was shown to be useful in the estimation of soil water retention properties. The studied geological materials correspond to the phyllites, quartz-phyllites, metagreywackes, quartzites, schists and granites in the Northern part of Portugal. The source of information used to carry out this study was the soil map of the studied region, scale 1/25,000. Non-parametric Kruskal-Wallis tests, followed by multiple comparisons between pairs of group medians using Bonferroni significant differences (BSD), were applied to determine if soil texture heterogeneity, measured using the BEI, significantly varied between the lithological groups under study. Results clearly show how the type of rock controls the BEI of the overlying soils in the studied area. Further implications of this result are discussed in the text.

4.1. INTRODUCTION

Geological material is one of the main soil forming factors along with climate, organisms, topography and time (Jenny, 1941). The nature and composition of the parent material influences the physical properties of the overlying soil, such as particle size distribution (PSD) or hydraulic properties. Soil hydraulic properties are needed for various purposes in hydrology, agriculture, environmental sciences, and civil engineering, but direct measurements are laborious, time-consuming and expensive. As a result, soil hydraulic parameters are rarely quantified in the majority of soil surveys databases. Nowadays, the development and use of pedotransfer functions to estimate soil hydraulic properties from basic data available from soil surveys is common. Soil PSD, or texture, is a complex distribution usually reported in terms of the mass percentage of clay, silt and sand, which is known to be a leading property affecting soil hydraulic properties. Consequently, soil texture fractions have been widely used as predictor variables in most of the pedotransfer functions proposed to estimate the soil water characteristics (Saxton et al., 1986; Pachepsky and Rawls, 2004; Patil and Singh, 2016). This work tries to bridge the conceptual distance between the geological material of the Earth's surface and the soil hydraulic properties of the overlying soils by studying the relationships between the parent material characteristics and PSD parameters which have been shown to be useful in estimating soil water retention properties.

Shannon (1948a,b) introduced a general measure of uncertainty commonly known as "Shannon entropy", which considers different probabilities of states of a system and can be applied to the characterization of the evenness of statistical distributions, such as the PSD. If a probability distribution is described with N class intervals, the Shannon Entropy (H) is computed as

$$H = - \sum_{i=1}^N p_i \log p_i \quad (4.1)$$

where p_i is the probability of the random variable to be in the i th interval. H has been used in soil science to characterize the soil particle size distribution (Martín and Taguas, 1998), the development and distribution of soil horizons (Phillips, 2000), to derive a soil entropy measure of soil pore size distribution (Yoon and Giménez, 2012) and more recently to assess pedodiversity in upscaling soil maps (Constantini and L'Abate, 2016).

Shannon entropy serves as an efficient measure of the evenness of distributions when all class intervals are equal, but that is not the case of soil texture fractions where soil particle size intervals vary significantly between classes: 0.002 mm in clay fraction; 0.048 mm in silt fraction; and 1.950 mm in sand fraction, according to the USDA classification (Soil Survey Division Staff, 1993).

Martín et al. (2001) introduced the Balanced Entropy Index (BEI) as a measure of soil texture heterogeneity, where H is normalized using a multiplier that explicitly reflects the different particle size intervals of soil texture fractions. Thus, BEI can be assumed as a generalization of Shannon entropy introduced as a measure of the evenness of a distribution with respect to a range of unevenly classified size (Rey et al., 2006). The BEI proposed by Martín et al. (2001) is given by the following formula

$$BEI = \frac{\sum_i p_i \log p_i}{\sum_i p_i \log l_i} \quad (4.2)$$

where p_i is the mass proportion of the clay-silt-sand fractions and l_i is the proportion of the i th class size interval in the total range of sizes ($l_1=0.001$ for clay, $l_2=0.024$ for silt, and $l_3=0.975$ for sand). This BEI takes values from 0 to 1 depending on the mass percentages represented by the clay-silt-sand fractions (Fig. 4.1).

Fig. 4.1. Soil texture triangle with BEI values obtained from the clay-silt-sand fractions

It is noteworthy that BEI can also be calculated considering more soil fractions along with their corresponding interval size lengths. Changes in the number of soil size fractions and also in the interval lengths of those fractions significantly alter the range of BEI values, and this should be taken into account before comparing BEI results obtained from PSD based on different fraction size systems.

The use of BEI was recognized as a promising approach to improve the accuracy of estimated soil hydraulic properties (Martín et al., 2005b). In the cited work, the BEI was tested as predictor of soil water content at different soil water potentials along with other fractions of textural components and organic carbon by applying data mining techniques on a dataset of 9871 soil samples. Since then, the BEI was applied to test the continuity of field soil particle size distributions (Rey et al., 2006), and to establish quantitative relationships between hydrological and pedological properties at different scales (Cámara et al., 2015).

Considering that BEI could potentially been used to understand and predict the outcome of physical and hydrological processes in soil, this work explores how parent material influences the soil texture heterogeneity of the overlying soils. Metamorphic and granitic rocks of Northern Portugal constitute the exploratory area, and the soil map of the study area, scale 1/25,000, represents the only source of information.

4.2. MATERIALS AND METHODS

4.2.1. Study area

The study area is the Portuguese wine growing region called “Região Demarcada do Douro”, thereafter RD Douro, which is located in the Northern part of the country, covering 2,474 km² of four Portuguese districts: Vila Real, Bragança, Viseu and Guarda.

The study area was chosen because the contrasting geological materials of the region were suitable for the study purposes and secondly, and not less important, because of the availability of the soil map in digital format along with the associated database.

The area covered by the RD Douro belongs to the basin of the Duero River, which is one of the major water streams crossing Portugal.

The RD Douro is located in the Northwest sector of the Hesperian Massif and in terms of lithology it consists essentially of two types of rock: igneous rocks (granites) and metamorphic rocks (mainly phyllites, quartz-phyllites, and metagreywackes). Metamorphic rocks have major presence in the study region and occur in geological formations ranging from the Precambrian to Devonian in age.

According to the climatic information reported in the soil map, which was based on time series from 54 weather stations located within or near the RD Douro (Gómez-Miguel et al., 2011), the average annual rainfall in the study area is $687 \pm 188 \text{ mm} \cdot \text{yr}^{-1}$ (Mean $\pm$ Std. Deviation) and the annual average temperature is $14.4 \pm 1.3 \text{ }^{\circ}\text{C}$ (Mean $\pm$ Std. Deviation).

The temperate and subhumid climate creates excellent conditions to produce quality wines in the RD Douro. The vineyards cover 371 km^2 , which are located mostly in the steep and rocky terraced landscapes of the Duero River and its tributaries, but only 260 km^2 are authorized to produce the famed sweet 'Vinho do Porto'.

4.2.2. Soil map 1/25,000

The soil map of the RD Douro, scale 1/25,000, was created as a part of the research project “SUVIDUR: Sustainability of viticulture in the area of the Duero River”, integrated in the European International Cooperation Program between Spain and Portugal during the 2007-2013 period.

The soil map covers the $2,474 \text{ km}^2$ of the RD Douro. Soils are classified according to Soil Taxonomy at the series level (Soil Survey Staff, 2014). The map legend comprises 150 soil map units (SMUs) defining 27,259 differentiated units. SMUs are different combinations of the 211 soil taxonomic units (STUs) identified and classified within the study area at the series level. Each STU could represent the dominant, second, third, fourth, or even the fifth STU within each SMU, according to its relative weight in the SMU area. The soil map database includes morphological and analytical data from 1,217 soil profiles.

The major soil order in the study area are Entisols, followed far behind by Inceptisols. Entisols are major as dominant STU and second STU, while the presence of Inceptisols becomes relevant as third STU. Marginal presence of Mollisols and Alfisols completes the list of local soils (Table 4.1). The spatial distribution of the dominant STU is shown in Fig. 4.2. Soil information in Table 4.1 and Fig. 4.2 was grouped at the subgroup level of the Soil Taxonomy in order to make the information accessible and manageable.

Table 4.1. Area covered by the different soils in RD Douro at the subgroup level of Soil Taxonomy.

Taxonomic subgroup	Area covered as					
	Dominant STU		Second STU		Third STU	
Soil order	<i>km²</i>	%	<i>km²</i>	%	<i>km²</i>	%
Lithic Xerorthent	1244.98	50.65	598.43	24.35	109.04	4.44
Dystric Xerorthent	1109.60	45.15	1130.03	45.97	189.21	7.70
Typic Xerorthent	79.12	3.22	27.64	1.12	331.78	13.50
Anthraltic Xerorthent	6.50	0.26	538.96	21.93	722.35	29.39
Typic Xerofluvent	-	-	74.40	3.03	-	-
Entisols	2440.21	99.28	2369.47	96.40	1352.38	55.03
Lithic Humixerept	17.65	0.72	2.52	0.10	268.29	10.91
Dystric Humixerept	-	-	-	-	0.38	0.01
Entic Humixerept	-	-	84.38	3.44	543.82	22.13
Typic Humixerept	-	-	-	-	93.74	3.81
Typic Dystroxerept	-	-	1.49	0.06	188.28	7.66
Typic Haploxerept	-	-	-	-	9.00	0.37
Inceptisols	17.65	0.72	88.39	3.60	1103.51	44.89
Lithic Haploxeroll	-	-	-	-	0.46	0.02
Mollisols	-	-	-	-	0.46	0.02
Ultic Haploxeralf	-	-	-	-	1.49	0.06
Alfisols	-	-	-	-	1.49	0.06

The techniques used to establish new vineyards in the region, that involve the construction of new terraces in the steep and rocky hillslopes by grinding the parent material with heavy machinery, explain the significant presence of Anthraltic Xerorthents in the study area (Table 4.1).

Fig. 4.2. Soil map 1/25 000. Dominant STU represented at the subgroup level: Lithic Xerorthents (XonL); Dystric Xerorthents (XonD); Typic Xerorthents (XonT); Anthraltic Xerorthents (XonA); Lithic Humixerepts (HxpL); and water streams (Ws).

The lithological information comprised in the soil map was adapted from the Geological Map of Portugal, scale 1/50,000 (GMP), and more specifically, from the following sheets: Mirandela (7-C); Celorico de Basto (10-A); Vila Real (10-B); Peso da Régua (10-C); Alijó (10-D); Torre de Moncorvo (11-C); Carviçais (11-D); Lamego (14-A); Moimenta da Beira (14-B); Vila Nova da Foz Côa (15-A); Freixo de Espada a Cinta (15-B); and Figueira de Castelo Rodrigo (15-D).

The soil map includes information of 75 lithological groups (LGs), which define 4,671 differentiated lithological units (LUs). The 11 LGs with major presence in the region, each represented by more than 5 LUs, were selected to carry out the study (Table 4.2).

Table 4.2. Lithological groups of the region under investigation in this study

Code	Lithologic groups		Code on GMP	Area covered	
	Type of rock	Brief description			
				<i>km²</i>	<i>% RD DOURO</i>
I1	Igneous	Granite: medium grained, two-mica, not porphyritic	γl3c	167.86	6.83
I2	Igneous	Granite: medium to coarse grained, two-mica, porphyritic	γl3a	130.38	5.30
I3	Igneous	Granite: medium to coarse grained with sparse megacrystals, two-mica	γl4a	94.94	3.86
I4	Igneous	Granite: fine to medium grained, two-mica, not porphyritic	γl3b	65.46	2.66
I5	Igneous	Granite: medium grained, muscovite, porphyritic, with tourmaline	γl4f	61.24	2.49
M1	Metamorphic	F. Desejosa: chloritic phyllites with levels of metasiltites and metagreywackes	CDe	734.79	29.90
M2	Metamorphic	F. Pinhão: phyllites, chloritic quartz-phyllites, and metagreywackes	CPi	421.83	17.16
M3	Metamorphic	F. Rio Pinhão: metagreywackes and chloritic phyllites	NCRp	194.31	7.91
M4	Metamorphic	F. Quartzito Armoricano: upper and lower quartzites, with intermediate schists	OQA	91.31	3.72
M5	Metamorphic	F. Bateiras: chloritic phyllites, metagreywackes and quartz-greywackes	NCBa	89.64	3.65
M6	Metamorphic	F. Ervedosa do Douro: phyllites, chloritic quartz-phyllites and metagreywackes	CEr	95.70	2.67

Five LGs correspond to granitic rocks (I1 to I5) and six LGs to metamorphic rocks (M1 to M6). Table 4.2 shows a brief description of the 11 selected LGs, which are thoroughly described in the legend of the GMP. Table 4.2 also provides the corresponding code on the GMP for each LG. Selected LGs cover 86.15% of the RD Douro. The reduction of the LGs under study decreased the number of studied SMUs to 67. However, the comparison between Table 4.1 and Table 4.3 reflects that this simplification barely modified the presence of the different soil subgroups in the reduced area.

Table 4.3. Area covered by the different soil subgroups in the studied lithological groups

Taxonomic subgroup		Area covered as					
Soil order		Dominant STU		Second STU		Third STU	
		<i>km²</i>	<i>%</i>	<i>km²</i>	<i>%</i>	<i>km²</i>	<i>%</i>
	Lithic Xerorthent	1075.16	50.91	495.41	23.46	66.83	3.17
	Dystric Xerorthent	949.53	44.96	1011.34	47.89	148.94	7.05
	Typic Xerorthent	62.87	2.98	4.17	0.20	251.12	11.89
	Anthraltic Xerorthent	6.50	0.31	491.37	23.27	637.15	30.03
	Typic Xerofluvent	-	-	53.82	2.55	-	-
	Entisols	2094.06	99.16	2056.11	97.37	1101.04	52.14
	Lithic Humixerept	17.65	0.84	-	-	238.91	11.31
	Entic Humixerept	-	-	55.60	2.63	521.91	24.71
	Typic Humixerept	-	-	-	-	93.68	4.43
	Typic Dystroxerept	-	-	-	-	154.75	7.33
	Typic Haploxerept	-	-	-	-	1.44	0.07
	Inceptisols	17.65	0.84	55.60	2.63	1010.67	47.86

According to Table 4.2, dominant rocks in the study area are phyllites, quartz-phyllites, metagreywackes and granites. The geotechnical characterization of phyllites and metagreywackes of the studied region was provided by Andrade et al. (2010). The characterization of the weathering properties of the regional granites can be found in Sequeira Braga et al. (2002).

4.2.3. Lithologic control on BEI

The effect of bedrock lithology on BEI was analyzed using two different methods. With the first method, soil samples in the database were grouped by the lithological group of the sample location, and the effect of bedrock lithology on BEI values was assessed through the analysis of variance of BEI values between LGs.

Fig. 4.3. Scheme of the method for aggregating the BEI values

The second method used additive properties of the entropy function and the known relationships in terms of probability or relative frequency of the different features of the soil map (LUs, SMUs, STUs, effective soil depth, horizon thickness), to provide an aggregated value of BEI for each lithological unit (BEI_{LU}) of the lithological groups under investigation (Fig. 4.3). This second methodology can be summarized in four steps as follows: (1) BEI is calculated with the mass proportion of clay, silt and sand for each soil horizon in the dataset; (2) the BEI of each STU (BEI_{STU}) is obtained weighting the BEI of the soil horizons in the STU with the proportion of the effective soil depth represented by the horizons thickness; (3) the BEI of each SMU (BEI_{SMU}) is calculated by weighting the BEI_{STU} according to the proportion represented by each STU within the SMU; and finally (4), the BEI of each LU (BEI_{LU}) is obtained weighting the BEI_{SMU} of the SMUs comprised in the LU with the proportion of the LU area covered by each SMU.

4.2.4. Statistical analysis

As BEI intra-group distributions mostly failed the different tests of normality, the differences of BEI values between lithological groups were tested using the non-parametric Kruskal-Wallis ANOVA test, followed by multiple comparisons between pairs of group medians using Bonferroni significant differences (BSD) at statistical significance of 95% ($p < 0.05$). All statistical tests were performed using the software Statgraphics Centurion XVII.

4.3. RESULTS

4.3.1. Univariate analysis of BEI

The results of the statistical analysis of the BEI values obtained for each soil sample in the soil map database are shown in Table 4.4. As the study area was reduced to eleven LGs, two populations of BEI values were studied: the first, represented by all BEI values in the database, and the second, which only involves BEI values corresponding to the selected LGs.

Table 4.4. Univariate analysis of the BEI values for both populations; all the soil samples in the database, and the soil samples of the studied lithological group (LGs).

	Soil samples from	
	Complete database	11 selected LGs
Count	1510	1102
Mean	0.457	0.453
Standard deviation	0.085	0.087
Minimum value	0.178	0.178
Maximum value	0.707	0.707
Range	0.530	0.530
Standardized bias	4.313	5.754
Standardized kurtosis	-2.773	-2.117

Table 4.4 shows that the results of the statistical variables for both populations are practically equal. BEI values in both cases range from 0.178 to 0.707, which means that the reduction of the study area to the major 11 LGs does not reduce the range of BEI values analyzed. A noteworthy finding of this statistical analysis is that the standardized bias and the standardized kurtosis of the BEI variable are outside of the $[-2,2]$ range for both populations. Values outside of this range indicate that BEI distributions fail the test of normality, and therefore only non-parametric tests could be used to compare BEI values between different groups. In order to visualize the BEI distributions, the histograms of both populations were built classifying the BEI values in class intervals of 0.025 units (Fig. 4.4a).

Histograms in Fig.4.4a reaffirm the similarity between the studied populations of BEI values and illustrate how the distributions differ from normality.

Fig. 4.4. Histograms of BEI: a) BEI values calculated for each soil horizon, and b) aggregated BEI values for each lithological unit (BEI_{LU}).

4.3.2. Analysis of BEI values grouped by lithological groups

The statistical variables describing the BEI values within each LG are provided in Table 4.5. The Kruskal–Wallis test, that was applied to determine if BEI values significantly varied between LGs, rejected the null hypothesis of no difference between group medians ($p\text{-value} = 0$). Median values of BEI for each LG show significant differences between metamorphic and granitic lithologies. The median values of BEI in the metamorphic LGs (0.387-0.415) are significantly lower than in the granitic LGs

(0.546-0.582), which is consistent with previous works in other granitic and metamorphic regions of the Iberian Peninsula (Cámara et al., 2015). According to Fig.4.1, the median values of BEI in the granitic LGs correspond to coarser soil textures than values reported for metamorphic LGs.

Table 4.5. Univariate analysis of BEI values of soil horizons, grouped by lithological groups.

	Statistical variables					
	Count	Mean	Std. deviation	Min.	Max.	Median
I1	46	0.565	0.055	0.445	0.707	0.565 b
I2	63	0.571	0.067	0.293	0.691	0.582 b
I3	56	0.565	0.059	0.432	0.659	0.573 b
I4	58	0.564	0.061	0.378	0.688	0.574 b
I5	39	0.540	0.059	0.403	0.637	0.546 b
M1	338	0.420	0.064	0.256	0.625	0.415 a
M2	226	0.417	0.054	0.269	0.541	0.414 a
M3	141	0.434	0.064	0.251	0.650	0.432 a
M4	28	0.389	0.066	0.178	0.526	0.387 a
M5	59	0.414	0.060	0.228	0.537	0.415 a
M6	48	0.406	0.057	0.257	0.532	0.393 a

Different letters in a row indicate significant differences ($p < 0.05$). BSD test.

This result supports the main idea that parent material controls the PSD of the overlying soil, and recognizes the capability of the BEI to quantify this control and discriminate between geological materials. However, the BEI values of the overlying soils were only capable to discriminate between granitic and metamorphic LGs. No significant differences in BEI values appeared among the granitic LGs or among the metamorphic LGs.

According to Martín et al. (2005b), at equal soil water potentials, higher soil water contents are expected in metamorphic LGs.

4.3.3. Aggregated BEI_{LU} based on the soil map information

The BEI_{LU} was calculated, following the second methodology described in the previous section, for the 251 LU belonging to the studied LGs. Table 4.6 shows the statistical variables describing the BEI_{LU} values grouped by LG.

Table 4.6. Univariate analysis of BEI_{LU} values grouped by lithological groups.

	Statistical variables						
	Count	Mean	Std. deviation	Min.	Max.	Median	
I1	22	0.569	0.005	0.553	0.573	0.571	d
I2	16	0.557	0.005	0.547	0.565	0.557	d
I3	17	0.540	0.013	0.522	0.569	0.535	d
I4	16	0.549	0.007	0.538	0.565	0.549	d
I5	17	0.566	0.007	0.559	0.588	0.563	d
M1	36	0.429	0.012	0.395	0.446	0.433	bc
M2	47	0.406	0.005	0.398	0.426	0.405	a
M3	49	0.434	0.009	0.413	0.447	0.436	c
M4	11	0.427	0.004	0.420	0.431	0.429	abc
M5	7	0.402	0.001	0.400	0.403	0.402	ab
M6	13	0.407	0.005	0.398	0.412	0.409	ab

Different letters in a row indicate significant differences ($p < 0.05$). BSD test.

In this case, the Kruskal–Wallis test was applied to determine if BEI_{LU} values significantly varied between LGs, and again the null hypothesis of no difference between group medians was rejected (p -value = 0). Significant differences in BEI_{LU} values were identified between metamorphic and granitic LGs, and among metamorphic LGs. However, according to the available characterization of the LGs, it was not possible to assign these statistical differences to specific properties of the LGs. Median values of BEI_{LU} in the metamorphic LGs range from 0.402 to 0.436, while in the granitic LGs range from 0.535 to 0.571. As a result of the aggregating method to obtain BEI_{LU} , the standard deviation of BEI_{LU} among LGs is significantly lower than the standard deviation among LGs of the individual BEI values.

Aiming to visualize the distributions of BEI_{LU} values for metamorphic and granitic LUs, histograms were built classifying the BEI_{LU} values in class intervals of 0.0125 units (Fig.4.4b).

Figure 4.4b shows how metamorphic and granitic LUs constitute independent populations according to the aggregated BEI_{LU} results.

4.4. DISCUSSION

Soil formation, sensu stricto, is the transformation of the parent material of the soil system into the soil mantle (Targulian and Krasilnikov, 2007). In temperate

climates, the influence of geological material on PSD is expected to be greater in soils poorly developed on steep and rocky areas than in other soils with well-developed genetic horizons, where pedogenic processes (e.g. clay eluviation/illuviation) have modified the PSD of soil horizons. The major influence of parent material properties on soil PSD has been reaffirmed in recent studies on Pseudogley soils (IUSS Working Group WRB, 2006) in Croatia (Rubinić et al, 2015), and on Typic Dystrudepts (Soil Survey Staff, 2014) developed from granites in France (Mareschal et al., 2015).

Soil maps are used as source of information in many studies related to agriculture, hydrology, and environmental sciences. The map scale of the soil map of RD Douro seems to be suitable for study purposes according to Leenhardt et al. (1994), who affirmed that soil classification at scale 1/25 000 effectively partitions the variance of soil physical properties.

However, the management of the information contained in soil maps at general scales is a nontrivial task that requires extensive prior knowledge. In order to simplify this management, only the dominant STU is taken into account in some studies (Hiederer and Köchy, 2011; Phillips, 2016), or directly, monotaxic SMUs are used at general scales (Behrens et al., 2010). The methodology followed in this work for the calculation of BEI_{LU} takes into account all the available information in the soil map corresponding to each LU, which preserves the soil map pedodiversity in the aggregated parameter. Ignoring the regional variation in the proportions of STUs within the SMUs constitutes a common source of error in the interpretation of soil maps. The proposed method for BEI_{LU} calculation provides regional variations among lithological groups, which represents one of the detected advantages of this approach.

A weakness found in this study, which is common in most studies using geological maps, is that qualitative description of geological map units can hardly be used to establish clear differences between lithological groups showing similar characteristics. This happens in this work (Table 4.2) in the metamorphic LGs (M1, M2, M3, M5 and M6) because phyllites and metagreywackes can vary significantly in their mineralogical and textural composition, sometimes within a matter of centimeters, and specially, among the granitic LGs (I1, I2, I3, I4 and I5) which do not show contrasting characteristics (e.g. in bedrock grain size). Thus, the main influence of granite grain size on PSD suggested by Mareschal et al. (2015) could not be verified in our study area.

After studying the influence of bedrock lithology on the Balanced Entropy Index using two different methods, we can confirm that in the studied conditions the soil texture heterogeneity is controlled by the type of rock that constitutes the soil parent material. As BEI is useful in estimating soil water retention properties (Martín et al., 2005b), the results of this study could have implications in watershed hydrology that further research should explore.

4.5. CONCLUSIONS

The lithologic control of soil texture heterogeneity was explored in the phyllites, quartz-phyllites, metagreywackes, quartzites, schists and granites existing in the Região Demarcada do Douro, in Northern Portugal. The soil map of the region scale 1/25,000, which was created according to the USDA soil survey manual at the series level (Soil Survey Division Staff, 1993), was the only source of information used to carry out the study, and the soil texture heterogeneity was measured using the Balanced Entropy Index (BEI) proposed by Martín et al. (2001).

Two different methods using the soil map information were applied to study the influence of bedrock lithology on BEI, and non-parametric analysis of variance were performed to determine if BEI significantly varied among the lithological groups (LG) under study.

Results of both methods show how the type of rocks that constitute the soil parent material of the study area effectively controls the soil texture heterogeneity of the overlying soil.

Soils developed from metamorphic rocks revealed lower BEI values than soils developed from granitic rocks. Bearing in mind the potentiality of the BEI for understanding and predicting the outcome of physical and hydrological processes in soil, further research is suggested to investigate the likely implications that these results could have in watershed hydrological modeling.

GENERAL CONCLUSIONS

Complex structures within the studied landscape systems are strongly influenced by the properties of the underlying parent material. The quantification, in areas with contrasting parent materials, of patterns of complexity related to the pathway, storage and release of water across the landscape system have evidenced lithologic controls on complex structures of the system at different spatial scales.

Complexity measurements such as fractal and entropy parameters have been successfully applied to quantify patterns of complexity within the hydrologic and the soil systems. Fractal parameters effectively describe the complexity involved in both the geometric structure at landscape scale of the drainage networks, and in the spatial distribution of subsets of these hierarchical networks as the ones represented by first-order streams. The characterization of drainage networks in different areas with granitic and metamorphic rocks using the fractal box-counting dimension has represented a quantitative evidence of the lithologic control on these geometric patterns. In contrast, the influence of parent material on the soil system has been highlighted at a very different spatial scale, being studied in the mass distribution of the soil particles smaller than 2 mm. The balanced entropy index has allowed the quantification of the heterogeneity of the soil particle size distributions and, in turn, the identification of the lithologic influences in the complex patterns reflected within the soil texture.

Beyond illustrating the influence of parent material on the drainage system of the landscape, the quantification of the drainage network architecture using fractal parameters, along with another parameter of classical fluvial geomorphology as the drainage density, has enabled the proposal of a statistical classification model to identify some characteristics of the parent material underlying the landscape system. This model has been only tested in our study area but it suggests that the geometric structure and the scaling properties of the drainage networks automatically generated from medium-resolution digital terrain models are potentially useful to numerically identify properties of the parent material crossed by the drainage network, such as the type of rock.

The quantitative relationship between patterns of complexity at different scales of the landscape system has been addressed in this research. Only weak relationships could be established between the complex geometry of the drainage network and the

heterogeneity of the soil particle size distribution. However, from our point of view, the mere identification of quantitative relationships among so different scales and scenarios represents a significant result. This result was achieved only taking into account the soil texture heterogeneity of surficial soil samples, but the last chapter points out that the lithologic control on soil texture heterogeneity is better reflected considering the particle size distributions of every soil layer within the soil profile. The inclusion of this consideration in future works could bring clearer evidences of the suggested relationship between the studied patterns of complexity.

Innovative uses of available geographic databases have been applied for acquiring novel information about the landscape system. A topographic database, the 5-m resolution LiDAR digital terrain model, is the input of the proposed methodology for the identification of the parent material, which is based on the scaling properties of the drainage network. Furthermore, the semi-detailed soil map of the study area, scale 1/25000, and all the levels of information encompassed therein are used in the aggregating method of soil properties proposed in the last chapter for detecting the influences of parent material on soil texture heterogeneity.

The fact that parent material controls patterns of complexity intimately related to the landscape water flux suggests that lithological units with homogenous parent material could behave as hydrologic functioning units at landscape scale. Further research should include hydrological and meteorological data in order to confirm or refuse this suggestion, and to evaluate potential influences of patterns of complexity on the watershed behavior.

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