INSTITUTO SUPERIOR DE AGRONOMIA
Universidade de Lisboa

THE NATIONAL ECOLOGICAL NETWORK AND A LAND MORPHOLOGY MODEL

An application to Portugal

NATÁLIA SOFIA CANELAS DA CUNHA

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THESIS PRESENTED TO OBTAIN THE DOCTOR DEGREE IN LANDSCAPE ARCHITECTURE

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Natália Sofia Canelas da Cunha

Lisboa, 25 de Maio de 2017

To my family

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RESUMO

Uma das questões mais complexas que a sociedade moderna enfrenta é a transformação da paisagem, sua fragmentação e simplificação ecológica, e consequente perda de biodiversidade e degradação da qualidade dos ecossistemas. A Estrutura Ecológica (EE) tem sido vista como uma ferramenta para aumentar a conectividade ecológica dos ecossistemas e a biodiversidade, retomando a abordagem ecossistémica do "continuum naturale". Esta investigação pretende clarificar o potencial da EE no contexto do ordenamento do território e a sua importância e função dentro do conceito de Infraestrutura Verde (IV), emergente da Estratégia da UE para a Biodiversidade até 2020, como uma estrutura planeada e estratégica com múltiplas funções para a sociedade. Pretende também contribuir para a lacuna existente a nível nacional de cartografia dos sistemas ecológicos. Os principais objectivos de investigação são: 1) Desenvolver uma metodologia de delimitação da Estrutura Ecológica à escala Nacional (EEN) para Portugal continental e 2) Desenvolver e aprofundar um modelo de delimitação da Morfologia do Terreno (MT) a nível nacional. A MT classifica e representa a posição e função dos sistemas naturais na paisagem, podendo por isso contribuir para a análise e representação dos ecossistemas e dos seus serviços.

Esta tese contribui para a compreensão: i) da EEN como uma infraestrutura espacial, planeada enraizada em critérios de avaliação ecológica a nível nacional, definindo áreas, existentes e potenciais, de conectividade ecológica, fornecendo as condições físicas e biológicas necessárias para a conservação e/ou restauro das funções ecológicas da paisagem; ii) da importância da EEN como ferramenta de interpretação de base ecológica que permite um ordenamento e gestão sustentável do território, a várias escalas, fortalecendo as noções de conectividade e multifuncionalidade da paisagem, bem como o aumento de biodiversidade e a utilização sustentável dos recursos naturais; iii) da utilização da MT na delimitação das formas de relevo portuguesas, como uma importante ferramenta no planeamento, que contribui para a leitura e avaliação do funcionamento ecológico da paisagem e iv) da delimitação dos ecossistemas ribeirinhos, à escala nacional, na clarificação de conceitos relacionados com os recursos hídricos e na identificação e protecção das áreas com risco de inundação.

Palavras-chave • Infraestrutura Verde • Estrutura Ecológica • Ordenamento do Território • Morfologia do Terreno • Risco de inundação • Portugal.

ABSTRACT

One of the most complex issues that modern society is facing is landscape transformation, its fragmentation and ecological simplification, resulting in loss of biodiversity and a decline in ecosystems' quality. Recently, the concept and establishment of Ecological Networks (EN) have been seen as a solution towards nature conservation strategies targeting biodiversity and ecological connectivity, (re)focusing on the ecosystem approach and the "continuum naturale". The research in this dissertation aims to clarify the potential of EN in the context of landscape planning and its importance and function within the Green Infrastructure (GI) concept, emerging from EU Biodiversity Strategy to 2020, as a fundamental strategically connected infrastructure of abiotic and biotic systems underlying the provision of multiple functions valuable to society. It also addresses the lack of mapping at the national level of ecological systems. The main research objectives are: 1) To develop a methodology to map the National Ecological Network (NEN) for mainland Portugal and 2) To develop a Land Morphology (LM) mapping method at the national level. LM classifies landforms according to their hydrological position in the watershed and represents a helpful evaluation tool for modelling natural systems.

This thesis contributes to the understanding of: i) the NEN as a spatial network that defines areas of existing and potential ecological connectivity at various scales which provides the physical and biological conditions necessary to maintain or restore landscape' ecological functions; ii) the importance of NEN as an ecologically based tool towards a more sustainable landscape planning, strengthening the notions of connectivity and multi-functionality of landscape; iii) the morphological approach to map Portuguese landforms as valuable tool to assist policy makers and planners in taking decisions based on a more thorough analysis of land value and its ecological functions; and iv) Mapping the wet system at national level may have an impact on clarifying concepts related to water resources and can be used as a preliminary delimitation of floodplains and potential flood risk areas.

Keywords • Green Infrastructure • Ecological Network • Landscape Planning • Land Morphology • Flood risk • Portugal

RESUMO ALARGADO

Uma das questões mais complexas que a sociedade moderna enfrenta é a transformação da paisagem, a sua fragmentação e consequente perda de identidade, simplificação ecológica e degradação dos ecossistemas. Estas mudanças estão relacionadas com o aumento da população e alteração do uso do solo, particularmente com o abandono da terra, a urbanização incluindo infraestruturas de transporte, e os padrões de consumo e lazer. Como refere Telles (2003), não podemos separar a paisagem, nem simplificá-la em nome do crescimento económico, reduzindo a fertilidade e a qualidade do solo e da água. Desta questão surge o problema da protecção, conservação e salvaguarda dos recursos naturais e da conectividade ecológica.

Neste contexto, a necessidade de criar continuidades verdes tornou-se reconhecida desde o século XIX com o conceito de corredores verdes, de "greenways" no séc. XX, até ao conceito pós-moderno de multifuncionalidade da paisagem, promovido pela Convenção Europeia da Paisagem em 2000. Paralelamente, a partir dos anos sessenta do século XX emergiu uma nova sensibilidade para os problemas ambientais que conduziu à noção de conservação da natureza, materializada na criação de áreas protegidas. Em 1987, no Relatório Brundtland, esta atitude é alargada em nome do conceito de desenvolvimento sustentável aplicado às políticas de ordenamento do território. O projecto "Millennium Ecosystem Assessment" (MEA, 2003; Pereira et al., 2004) desenvolveu esta ideia numa tentativa de integrar o crescimento económico com o planeamento de base ecológica. Hoje em dia, sabe-se que as áreas protegidas, por si só, não fornecem uma gestão adequada à protecção do equilíbrio ecológico da paisagem, a longo prazo. No que respeita à biodiversidade, o facto de cerca de 82% do território da UE estar fora da Rede Natura 2000 (CE/CIRCABC, 2012) prova esta conclusão. Por outro lado, verifica-se que, em muitas cidades europeias, os habitats naturais estão fragmentados e degradados. A evolução das políticas Europeias, depois de um recuo nas políticas de conservação da natureza, passa a incidir novamente num âmbito mais vasto, admitindo que a conservação da biodiversidade exige uma estrutura física de suporte. Desta forma, a Estrutura Ecológica (EN) tem sido vista, recentemente, como a solução para aumentar a conectividade ecológica dos ecossistemas e a biodiversidade, retomando a abordagem ecossistémica do "continuum naturale" (Cabral, 1980), indo ao encontro das necessidades e dos desafios recentes quanto à gestão sustentável dos ecossistemas, emergentes na Estratégia de Biodiversidade da UE para 2020 e no novo conceito de Infraestrutura Verde (IV).

Esta pesquisa pretende esclarecer o potencial da EE no contexto do ordenamento do território e particularmente a sua importância e função dentro da nova abordagem da IV. À semelhança da prática registada em outros países, a EE foi incluída no regime jurídico português em 1999, de acordo com o qual deve ser considerada, delimitada e implementada em todas as escalas de planeamento. No

entanto, na aplicação da lei, o Programa Nacional de Política de Ordenamento do Território (PNPOT) não inclui nenhuma delimitação da EE a nível nacional e os planos regionais e municipais têm delimitações inconsistentes.

Outra prioridade da Agenda das Nações Unidas para o Desenvolvimento Sustentável 2030 e do Compromisso para o Crescimento Verde adoptado em 2015 pelo Governo Português, inscrita na revisão da Estratégia Nacional de Conservação da Natureza e da Biodiversidade, é o mapeamento e avaliação de ecossistemas e dos seus serviços. Este mapeamento deve basear-se na compreensão da Morfologia do Terreno (MT), entre outros factores, ou seja, na posição e função dos ecossistemas na paisagem. A MT constitui um instrumento de análise e representação da forma global do terreno, caracterizada pelas suas principais situações ecológicas de base física, nomeadamente hidrológica. A identificação dos sistemas, húmido e seco, e dos seus componentes, contribui assim para a compreensão do funcionamento ecológico da paisagem, no que respeita à disponibilidade hídrica, à formação de solo e distribuição de nutrientes, ao escoamento do ar e à vegetação potencial. Um dos problemas na sociedade, relacionado com a degradação dos ecossistemas, são as cheias e vulnerabilidade crescente das áreas inundáveis.

Neste contexto, com esta pesquisa pretende-se contribuir para a lacuna existente a nível nacional de cartografia dos sistemas ecológicos, numa perspectiva da sua utilização no ordenamento do território e respectivas políticas públicas, dando resposta às seguintes questões: • Como se relaciona a EE com o conceito de IV? • Como é que a EE pode ser delimitada a nível nacional integrando as componentes físicas e biológicas da paisagem? • Como se relacionam as características morfológicas com as demais características físicas na paisagem? • Como é que a Morfologia do Terreno pode ser aplicada no ordenamento do território e na delimitação das áreas de risco de inundação?

Esta tese inclui 6 capítulos, uma breve introdução ao tema, um enquadramento teórico com a revisão da literatura sobre Estrutura Ecológica, Infraestrutura Verde e Morfologia do Terreno, três capítulos compreendendo o desenvolvimento da tese em três artigos, uma conclusão. Tem como principais objetivos de investigação:

- Delimitar a EE à escala nacional (EEN) para Portugal continental. A metodologia é fundamentada no Sistema-paisagem (Magalhães et al., 2007) desenvolvida a nível municipal e está inserida no projecto de investigação (FCT-PTDC/AUR-URB/102578/2008) Estrutura Ecológica Nacional: proposta de delimitação e regulamentação desenvolvido no CEAP/ISA/Universidade de Lisboa. No âmbito deste projecto foi desenvolvido o estudo e interpretação das componentes da EEN, tendo a autora sido responsável pela tarefa da Morfologia do Terreno e da metodologia de delimitação da EEN, e co-responsável pelas tarefas das componentes Água e Litoral.

Este trabalho representa a primeira tentativa de delimitar a EEN portuguesa como uma estrutura espacial planeada, enraizada em critérios de avaliação ecológica a nível nacional. Esta rede fornece as condições físicas necessárias para manter e/ou restaurar as funções ecológicas, apoiar a biodiversidade, bem como a utilização sustentável dos recursos naturais. A metodologia é composta por dois sistemas principais: um sistema físico que se refere às componentes geologia/litologia, solo, água e clima e um sistema biológico constituído pelos habitats, flora e vegetação, e à sua interacção com as componentes do sistema físico. Foi utilizado um modelo integrado baseado num SIG para implementar a metodologia de delimitação da EE à escala nacional (EEN), a fim de identificar, mapear e priorizar essas áreas essenciais. A inovação deste estudo refere-se à selecção e identificação das componentes físicas e biológicas e aos métodos de avaliação e mapeamento, individuais e relacionais. A EEN foi hierarquizada em dois níveis de acordo com a sensibilidade ecológica e função de cada sistema/componente, em que o primeiro nível (EEN1) representa os ecossistemas mais “valiosos” em termos de biodiversidade e estabilidade do ecossistema, o que significa também que são os mais vulneráveis à actividade antrópica e, deste modo, as áreas mais sensíveis (ex. sistema húmido, solos de elevado valor ecológico, vegetação natural e semi-natural com elevado valor de conservação). Os resultados mostram que a maioria das componentes ecológicas não se sobrepõem e que a EEN1 abrange um total de 67 % da área de Portugal continental onde, em 2016, apenas 25 % estava legalmente protegido pelas áreas de conservação da natureza. Estes números permitem concluir que os critérios utilizados nas áreas de conservação, de facto, são insuficientes para salvaguardar os recursos naturais, assegurar o equilíbrio ecológico e evitar a fragmentação da paisagem. A EEN para Portugal continental e as respectivas componentes estão disponível online em http://epic-webgis-portugal.isa.ulisboa.pt/.

Relativamente à EEN, esta tese contribui para o seu entendimento como: i) uma estrutura planeada, concebida e gerida para diversos fins assente em componentes ecológicas que fornecem as condições físicas e biológicas necessárias à manutenção ou conservação das funções ecológicas; ii) uma ferramenta de interpretação de base ecológica que permite um ordenamento e gestão sustentável do território assente em usos múltiplos ou alternativos. Deste modo o conceito de EEN encerra um carácter mais propositivo do que restritivo afirmando o carácter (infra) estruturador do território contribuindo para o conhecimento das potencialidades do território e dos usos adequados, quer no espaço urbano quer rural. Deve por isso constituir uma “infraestrutura” fundamental de todos os planos de ordenamento, às escalas nacional, regional e municipal, e desenvolvida num contexto económico e social, a EEN é um importante contributo para Infraestrutura Verde de Portugal.

- Desenvolver e aprofundar um modelo de delimitação da Morfologia do Terreno (MT) à escala nacional, com base no conceito de Magalhães (2001). Neste estudo, os critérios de delimitação (Magalhães et al., 2002; Cunha, 2008) foram aprofundados e aplicados à escala nacional para Portugal continental, com validações a escalas de maior pormenor (escala regional e municipal). Este método relaciona as características topográficas e físicas da paisagem, como o declive e a hidrografia. Os resultados são comparados e discutidos com a distribuição de solos férteis (FAO, 2001) e com dois métodos de classificação automática do terreno: TPI (Weiss, 2001; Jenness, 2006) e MoRAP (True, 2002).

Neste sentido, a delimitação dos ecossistemas ribeirinhos à escala nacional e a sua comparação com dados de risco de inundação da Agência Portuguesa do Ambiente (APA) para os principais rios de Portugal continental irá contribuir para compreender o papel da delimitação do sistema húmido na identificação e protecção das áreas inundáveis e com risco de inundação. Este estudo concorre também para o esclarecimento do vasto número de conceitos ligados aos recursos hídricos nomeadamente no que se refere às zonas adjacentes, zonas ameaçadas pelas cheias e zonas inundáveis e para a delimitação dessa figura jurídica no Domínio Publico Hídrico (DPH) e na Reserva Ecológica Nacional (REN) no que refere à prevenção de riscos naturais.

Finalmente, este estudo realça a importância do desenho na gestão da paisagem e da EEN e MT como instrumentos de planeamento de base ecológica que contribuem para o conhecimento das potencialidades do território. Pretende-se assim, através da implementação futura da EE e de propostas de ordenamento elaboradas com base na aptidão/adequação ecológica, equacionar a complexidade e dinâmica da Paisagem com a protecção dos recursos naturais, de modo a promover a biodiversidade paralelamente com o aumento da qualidade de vida das populações e a necessária diminuição de riscos ambientais (inundações, incêndios florestais, erosão do solo, entre outros).

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APA	Portuguese Environmental Agency
DGT	Portuguese State Territory Authority
DPH	Public Hydric Domain
DTM	Digital Terrain Model
EECONET	European Ecological Network
EN	Ecological Networks
ERPVA	Regional Structure Plan for Environmental Protection and Enhancement
ES	Ecosystem Services
GI	Green Infrastructure
GIS	Geographic Information Systems
INAG	National Water Institute
LANMAP1	Pan-European Landscape Map
LANMAP2	European Landscape Typology Map
LM	Land Morphology
LMC	Land Morphology Concept
LMM	Land Morphology Mapping
MoRAP	Missouri Resource Assessment Partnership
NEN	National Ecological Network
NEN1	National Ecological Network Level 1
NEN2	National Ecological Network Level 2
NSCA	National System of Classified Areas
PEBLDS	Pan-European Biological and Landscape Diversity Strategy
PEEN	Pan-European Ecological Network
PMOT	Municipal Land Management Plan
PNPOT	National Program for Land Planning Policy
PROT	Regional Land Management Plan
RAN	National Agricultural Reserve
REN	National Ecological Reserve
RFCN	Fundamental Network of Nature Conservation
TPI	Topographic Position Index
WS	Wet system

“Nature doesn't mind what method you use to adapt, but adapt you must.”

Ian McHarg (1967)

1 | INTRODUCTION

1 | INTRODUCTION

One of the most complex issues that modern society is facing is a fast landscape transformation and its consequent fragmentation (Jaeger et al, 2011; Tillmann, 2005). The multiple changes are linked to population density and growth, land abandonment, urbanization and consumption patterns. These factors affect mainly land use, and result not only in the loss of landscape character (Meeus et al., 1990; Delbaere, 1998; Klijn, 2004; Antrop, 2005), but also in landscape fragmentation and homogenization. The result is a reduction in biodiversity and the decline of ecosystem quality (Mücher et al., 2010). As stated by Telles (2003), landscape cannot be considered partially nor solely as a function of economic growth. In neglecting soil fertility and water quality, the problem of protection and conservation of natural resources arises.

In this thesis, the concept of the 19th century green corridors and the post-modern concept of landscape multifunctionality, as promoted by the European Landscape Convention in 2000, are explored as they triggered a shift from the sectorial analysis approach of landscape planning, typical of modernism to a (re)focus on the ecosystem approach and “nature-based solutions” (EC, 2015).

Specifically, this thesis focuses on the need to establish Ecological Networks (EN) with ecological connectivity, which have became widely recognized within the Biodiversity Conservation Strategy in the 21st century. Under the Ecological Network concept and the European Union’s recent Green Infrastructure (GI) Strategy, the concept of landscape is regarded as a multifunctional dynamic resource, to which a wide range of ecosystem services are associated (EEA, 2014).

1.1 | Motivation and context

This research aims to clarify the role of ecological network (EN) and land morphology (LM) in landscape planning at a national level. Therefore, the main goal of this research is to better understand what Ecological Networks (EN) are, its importance and function within the 2015 GI framework, and to discuss how ecological systems can be mapped and modelled, via ecosystem’s location and function in the landscape.

This thesis is the result of nearly 15 years of research on EN and green planning, developed in the R&D Unit LEAF - Linking Landscape, Environment, Agriculture and Food /Research line “Green and Blue Infrastructures” (the former Research Centre of Landscape Architecture - CEAP), and coordinated by Professor Manuela Raposo Magalhães. As an integrated member since 2002, I had the opportunity to be involved in several research projects, namely Loures (2001-03), Almada (2002-03), Sintra (2004-08), Cinfães, Baião and Santo Tirso (2009-11) municipalities and Lisbon Metropolitan Area (Magalhães et al., 2003; Franco, 2011). I also have experience in teaching Biophysical Planning in the Environmental Engineering course at Instituto Superior Técnico/ Universidade de Lisboa (2004-2009) and in Landscape Planning at Instituto Superior de Agronomia/Universidade de Lisboa (2006-2012). During the past decade, I also participated in several workshops coordinated by Professor Christian Küpfer from Nürtingen University, Germany.

This doctoral project is embedded in the research project "National Ecological Network - a proposal of mapping and policies" (PTDC/AUR-URB/102578/2008) funded by Fundação para a Ciência e Tecnologia (FCT). Under this project, some case studies were developed, in which I was the scientific co-advisor (Franco et al., 2013; Ribeiro et al., 2013). The results of this work were further applied in the research project "Potential Land-Use Ecological Plan. Application to Portugal" (PTDC/AUR-URB/119340/2010) also financed by FCT.

1.2 | Problem statement and research questions

The impact of landscape fragmentation is a well recognized problem, in modern society that causes the degradation of ecosystems and the decline of European wildlife. Ecological Networks (EN) have been seen as the solution to this problem and were recently incorporated into the Green Infrastructure (GI) concept that emerged in both planning theory and policy. In this thesis, there is the need to clarify the potential of EN in spatial planning, especially its importance and function within GI. Linked to this, and according to EU and Portuguese policies, the EN must be implemented at all planning scales in order to define areas of existing and future (potential) ecological connectivity and value.

In Portugal, the EN concept was included in the legal system in 1999. However, Portuguese legislation still does not consider EN a unique entity nor addresses EN criteria for all planning scales. At the national level, the National Program for Land Planning Policy (PNPOT) does not include any EN maps, whilst the regional and municipal plans have inconsistent delimitations.

Moreover, mapping ecosystems is a priority in EU planning. Among other factors, mapping ecosystems and their services relies on an understanding of land morphology (LM), *i.e.* ecosystems location and function in the landscape, since LM directly influences surface water flow, the transport of sediments, soil genesis, topoclimate and vegetation distribution. Also related to LM, and a major environmental problem are floods. The increasing vulnerability of floodplains is connected to societal changes such as population growth, land use, water use patterns, among other factors.

In Portugal, population growth and urban sprawl in coastal areas, especially near floodplains, has been happening more intensely since the 1970's, as in Europe, and the number and costs of flood disasters have increased in the last four decades (EEA (2015). Despite having adopted EU water legislation, as part of Water Framework Directive and Floods Directive, there is some inefficiency in

Portugal's government and central institutions from a preventive and risk management perspective. Moreover, in Portuguese legislation, there are a large number of concepts related to water surface resources that are inconsistently defined and mapped.

This thesis will addresses the lack of mapping at national level on ecological systems and the following questions:

- How does Ecological Network (EN) relate to the concept of Green Infrastructure? What are EN components and their functions?
- How can EN be mapped at the national level by bringing together both the physical and biological components of the landscape? How can valuable ecosystems be mapped?
- How EN should be considered in the conservation strategies targeting biodiversity and ecological connectivity?
- How are topographic and other physical characteristics interconnected in landscape?
- How can Land Morphology (LM) be applied in land use planning and flood risk mapping?

1.3 | Aim and research objectives

This thesis aims to answer the questions mentioned above, namely by outlining the role of ecological networks and land morphology in landscape planning at a national level. Therefore, there are two main research objectives:

1) Develop a methodology to map the National Ecological Network (NEN) for mainland Portugal as a single entity. This NEN methodology is based on a multi-level ecological evaluation criteria which integrate, on two hierarchical levels, the physical and biological systems. These systems were studied independently and collectively at the national scale. The NEN criteria and maps presented, derived from a high spatial resolution dataset providing a spatial framework that can be replicable at all planning scales. This NEN methodology is based on the landscape-system concept previously applied at the municipal level (Magalhães et al., 2007), see Chapter 3 for details;
2) Develop a land morphology (LM) model based on Magalhães (2001). This LM model will provide an understanding of the ecological functioning of the landscape. The resulting LM map for Portugal will be a helpful tool to inform EN delimitation and flood risk mapping (see Chapter 4).

Within this research, the role of the wet system in flood risk management will be evaluated. The Portuguese river ecosystems will be GIS mapped and correlated with existing flood risk data from the Agência Portuguesa do Ambiente (Portuguese Environmental Agency), see Chapter 5. This will contribute to the Portuguese framework on water legislation, namely the Ecological Network Reserve (REN) that recently committed all municipalities to map flood risk areas at 1/25 000 scale.

1.4 | Dissertation structure

The thesis consists of three separate papers submitted for peer review. This thesis includes six chapters, comprising of a short introduction to the overall topic, a theoretical framework with a general literature review, various methodologies and a comparison, followed by a conclusion. A brief description of each chapter is found below:

Chapter 1 introduces the purpose and scope of this research and presents its structure.

Chapter 2 presents a state of art regarding key concepts such as Ecological Network, Green Infrastructure, and Land Morphology. Examples of the current status of national EN in countries in Europe are presented in Appendix A.

Chapter 3 describes a methodology to map the National Ecological Network (NEN) for mainland Portugal and the key guidelines for its implementation, through a multi-level evaluation. The EN is based on ecological criteria and considers two main systems: a) a physical system, including geology/geomorphology, land morphology, soil, water and climate components, and their interactions, b) and a biological system, comprising habitat and vegetation, and the interactions between them. The current Portuguese context of EN is also analyzed. This is presented broadly, in Portuguese, in Appendix B. Also, given that the mapping scale is a matter of significant importance, examples of the EN at the regional (Lisbon Metropolitan Area) and municipal (Lisbon) level are presented.

Chapter 4 presents a detailed study of the land morphology concept (LMC) and a mapping (LMM) method at the national level, as a component of EN. A literature review that covers trends in landform classification is presented. The method presented uses topographic and physical characteristics of landscape, derived from a combination of slope (specifically flat areas), surface curvature, and hydrological features. The results are compared and discussed in relation to fertile soil distribution, according to the FAO (2001) classification of wetland soil. The model developed was compared to two different automatic landform classifications: the TPI method (Weiss, 2001; Jenness, 2006) and MoRAP's landforms (True, 2002). An extended LM map with detail landforms classes is presented in Appendix C.

Chapter 5 explains floodplains as part of the wet system, in order to demonstrate its importance as a preliminary tool for delimitation and flood risk mapping. The morphological approach applied to map wet system (WS) at a national scale is discussed. The comparison between WS and flood risk data from the Portuguese Environmental Agency for the main rivers of mainland Portugal is made and discussed. A detailed study of an urbanized basin (Trancão river basin) is presented. Appendix D details the Portuguese legislation on surface water resources (in Portuguese).

Chapter 6 presents the overall conclusions, the thesis contribution to science and society and proposes further research.

2 | STATE OF THE ART

2 | STATE OF THE ART

In order to delve into the problem statement and the research questions identified in section 1, this section presents the relevant literature to understand the role of EN and land morphology (LM) in landscape planning at a national level. It addresses the concept of ecological network (EN), its legislative background, key principles and definitions, mainly within the Green Infrastructure (GI) framework, and provides the starting point to recognise land morphology (LM) as a helpful evaluation tool to inform EN delimitation and flood risk mapping.

2.1 | Ecological Network

The multiple changes in landscape transformation and its consequent fragmentation (Tillmann, 2005; Jaeger et al., 2011; Hagen et al., 2012) result not only in the loss of landscape character (homogenization) (Jongman, 2002) but also in the decline of European wildlife and the ecosystems quality and services (Mücher et al., 2010). The Ecological Networks (EN) should be considered as a solution towards nature conservation strategies targeting biodiversity and ecological connectivity, (re)focusing on the ecosystem approach and the "continuum naturale". For the last 40 years, the EN have been the focus of international research, policy and practice in landscape planning. EN is a fundamental strategically connected infrastructure of abiotic and biotic systems underlying the provision of multiple functions valuable to society.

Ecological Networks (EN) represent an effective political instrument and planning tool to counteract fragmentation (Fischer and Lindenmayer, 2007), by conserving and buffering core areas in terms of its natural/ semi-natural value, while maintaining and establishing ecological connectivity with different land uses (Magalhães, 2001; Magalhães et al., 2007; Čivić and Jones-Walters, 2015). In order to respond to the existing gap at the national Portuguese planning level, the following themes are further developed and discussed, in chapter 3: i) an ecologically based methodology for EN at the national level, ii) the EN components and functions, iii) a critical evaluation of EN in the existing Portuguese legislation, iv) and the key guidelines for EN implementation. Therefore, this section only addresses the EN concepts, the current policies and legislation at the international level and its integration within the GI approach.

2.1.1 Legislative background

The concept of EN was developed in the 1970s and 1980s in countries with a strong land use planning tradition (Bennet and Wit, 2001). An example of which is the *Estonian Network of Ecologically Compensating Areas* (see Appendix A) established in 1983 (Jagomägi and Sepp, 1999; Külvik et al., 2008). In Portugal, the EN was only incorporated into its legal system as late as 1999, although the concept was already in place under the designation of "continuum naturale" (Cabral, 1980) under the Environmental Framework Law (Law n. º11/87, updated by Law n.º 19/2014). The first Ecological Network designed under an EN concept was the Lisbon Ecological Network (Magalhães, 1993), included in the Lisbon Municipal Plan in 1994 (Telles, 1997). This development is further developed in chapter 3.

The EN is embedded within several policies, strategies at the European and international level (Harfst et al., 2010; Čivić and Jones-Walters, 2015), namely:

a) UNESCO's 1974 "Man and Biosphere Programme". It recognised the need to reconcile the conservation of valuable areas with local land-use needs through the delineation of core areas, buffer areas and transition zones. There are currently over 350 Biosphere Reserves;

b) The Birds Directive (79/409/EEC, 1979), the Bern Convention on Conservation of European Wildlife and Natural Habitats (Bern Convention, 1979) and the Habitats Directive (92/43/EEC, 1992) implementation of Natura 2000 site network across the EU member states and Emerald Networks (CE, 2009), established in 1996 at a pan-European level (2011-2020), consisting of areas of special conservation interest (ASCI);

c) The EECONET (European Ecological Network) declaration, endorsed by the European Union Treaty (1991) as a new policy instrument to ensure the successful implementation of the habitat Dirctive, has promoted a gradual development of EN in many European countries (Jongman, 1995). Within this EECONET framework the EN must: i) encompass important areas for the conservation of the biological and landscape diversity, ii) guarantee the maintenance of the ecological processes and the connectivity of the territory, iii) be incorporated into the planning of the territory, and iv) promote sustainable development (Bennet, 1991).

d) The Pan-European Biological and Landscape Diversity Strategy (PEBLDS) in 1995 (CE, 1996; Bouwma and Jongman, 1998) established:

- The Pan-European Landscape Map - LANMAP1 (Meeus, 1995; CE, 1996), updated in 2005, the European Landscape Typology Map - LANMAP2[1]. This map is a tool for European environmental assessment and policy implementation (Mücher et al., 2010; Jongman et al., 2011);
- The Pan-European Ecological Network – PEEN (Jongman et al., 2011; Biondi et al., 2012) indicates the core areas, buffer zones and corridors of the EN across Europe. It was built on a variety of existing initiatives, including Natura 2000, the European network of Biogenetic

[1]LANMAP2 is a high spatial resolution map at scale 1: 2M with a hierarchical classification with four levels and has 350 landscape types at its lowest level (level 4), which includes intertidal flats, urban conurbations and water bodies. Based on four classification criteria i) Climate (using the Environmental Classification and the Biogeographical Regions Map of Europe), ii) Topography (GTOPO30), iii) Parent material and ecological stand conditions (ESDB, FAO soil map), iv) Land use/cover (CORINE, PELCOM and GLC land cover) (Metzger et al, 2005; Wascher, 2005; Groom, 2005; Mücher et al., 2010).

Reserves, the EECONET concept, the Bern Convention, the Bonn Convention, and the many national and regional ecological networks already under development (UN, 2007). Between 1991 and 1995 the term EECONET was replaced PEEN but the basic concept remains the same: a Europe-wide EN of core nature areas, with elements that ensure connectivity (Rientjes and Roumelioti, 2003). It includes Central and Eastern Europe, South-Eastern Europe and Western Europe (Jongman et al., 2011; Jones-Walters, 2007).

e) The Water Framework Directive (2000/60/EC) commits European Union members to achieve good qualitative and quantitative status for all ground and surface waters (rivers, lakes, transitional and coastal waters). It is a water policy framework managed according to River Basin Management Plans, which are updated every six years. It establishes rules to halt deterioration and specifically, it includes: restoring those ecosystems in and around these bodies of water; reducing pollution in water bodies; and thus guaranteeing sustainable water usage by individuals and businesses (WFD, 2012).

f) The latest 2011 Biodiversity Strategy for 2020, under target 2, aims to halt the loss of biodiversity in the EU by 2020 and result in the recovery of at least 15% of degraded ecosystems (CE, 2011; Mazza et al., 2011; EC/CIRCABC, 2012).The Action 6b of this Strategy sets priorities to restore and promote the use of GI (detail in section 2.2).

2.1.2 Ecological Network concepts

Embedded in these policies, EN has been used in several contexts and scales, with different concepts. From a simple combination of features to a multi-objective tool, EN can be described, according to Bennet and Wit (2001) and Boitani et al. (2007). This is elaborated on Table 2.1.

The first and common EN definitions were originally planned to favour overall biodiversity conservation but in practice, the focus is on the needs of species whose habitat is assumed to be on a landscape scale (Čivić and Jones-Walters, 2015). More recently, the EN concept assumes a holistic view of land-use planning and biodiversity conservation and has been expanded to include webs of linkages for several different functions (ecological, social, political and cultural). The “Abiotic, Biotic and Cultural” (ABC) resource model (Ahern, 1995; Ahern, 2007) and the “Landscape-System” methodology (Magalhães, 1997; Magalhães et al., 2005, 2007) are examples of inclusive models or multi-objective tools that recognise the needs and mutual impacts of humans on biotic and abiotic systems and processes.

Table 2.1 Ecological Network concepts

EN concepts	Examples *
A simple assemblage of protected areas	Natura 2000 sites
Hubs and links between protected areas (Benedict and McMahon, 2002)	Wildlands Project - since 1991 is a large landscape-scale habitat connectivity in North America (www.wildlandsnetwork.org)
Core areas, corridors including stepping stones, buffer zones, and restoration areas (Bouwma et al., 2002; Bennett, 2004; Hong et al., 2007) as a network approach to nature conservation planning regarding the biological resources	PEEN - Pan-European Ecological Network (Jongman et al., 2011; Biondi et al., 2012) Estonia (Külvik et al., 2008); Netherlands (Hajer, 2003), Sweden (Sandström, 2002), Germany (Tiemann and Siebert, 2008; Hasse, 2010), Brazil (Herzog, 2010), New Zealand (Ignatieva, 2010); Czech Republic (Mackovčin, 2000; Plesník, 2008); Australia (Kilbane, 2013)
Reserve networks - a large-scale regional or continental "green backbones" that focus primarily on biodiversity conservation at the regional scale	The Yellowstone-to-Yukon Conservation Initiative (www.y2y.net)
Ecoregions – a WWF initiative that aims for the conservation of the world's key large units of land or water that harbour a characteristic set of species, communities, dynamics and environmental conditions	The Global 200 - 867 terrestrial ecoregions (Olson et al., 2001). An example is the Carpathian Ecoregion Initiative (Bennett, 2002) and the Iberian sclerophyllous and semi-deciduous forests - "montados" in Portugal and "dehesas" in Spain (PA1209)
Bioregions – Primarily developed by the World Resources Institute in the US and which concern large-scale geophysical patterns, is an ecologically and geographically defined area that is smaller than an ecozone, but larger than an ecoregion or an ecosystem.	Biogeographic Regionalisation for Australia (IBRA7, 2012)
Green continuities green belts, green corridors, greenways – linear open space established along either a natural corridor, or overland along a railroad, canal or other route converted to recreational use, (Flink and Searns, 1993; Ahern, 1995; Linehan et al., 1995; Fabos, 1995)	Emerald Necklace park system, Massachusetts designed by Frederick Law Olmsted (Ahern, 1995) Monsanto green corridor, Lisbon (Telles, 1997) The Florida Statewide Greenways Project (Hoctor et al., 2004) The German Green Belt (Riecken and Finck, 2012)
Ecological networks which encompass ecological, recreational and cultural heritage aspects (Ahern, 2007; Magalhães et al., 2007; Fischer and Lindenmayer, 2007)	USA (Fabos, 2004), UK (Turner; 1995; Catchpole, 2008; Mell, 2010), Lisbon Green plan (Magalhães, 1993) Maryland Plan Green Infrastructure (Weber et al., 2006)

* An overview of the EN examples is detailed in Appendix A

In this thesis, the EN is considered to be a spatial concept based and is a planned network, designed and managed for various purposes and recognised as a system of ecological components (Jongman and Pungetti, 2004; Magalhães, 2001). It provides physical conditions that are necessary for maintaining or restoring ecological functions, supporting biological and landscape biodiversity and promoting the sustainable use of natural resources (Forman, 1995; Bennett and Wit, 2001; Bennett, 2004; Hong et al., 2007; Bennett, 2010).

The definition adopted here was addressed in the "Landscape-System methodology" (Magalhães et al., 2007) as a spatial concept based on multi-level ecological and cultural evaluation criteria which integrate in a single framework the biophysical and cultural systems. The methodology presented for mapping the EN for mainland Portugal will focus on ecological components including the physical and biological systems (chapter 3).

2.2 | Green Infrastructure framework

In just over a decade, the Green Infrastructure (GI) concept has emerged in both planning theory and policy (EC, 2011; Mazza et al., 2011; EC, 2013) primarily employed in USA and UK (Allen 2014; Lennon, 2014; Mell, 2015; Baró et al., 2015), as "the network of natural and semi-natural areas, features and green spaces in rural and urban, terrestrial, freshwater, coastal and marine areas which together enhance ecosystem health and resilience, contributing to biodiversity conservation and benefiting human populations through the maintenance and enhancement of ecosystem services" (Naumann et al., 2011). The GI was formally endorsed by the European Commission (EC, 2013) in the EU Biodiversity Strategy to 2020 "Our life insurance, our natural capital" in its action 6b "Green Infrastructure Strategy: Enhancing Europe's Natural Capital" as "a successfully tested tool for providing ecological, economic and social benefits through natural solutions". It comprises natural and man-made, rural and urban elements and encompasses the EN, ensuring the ecological coherence of the Natura 2000 Network.

As mentioned before, it is very important to integrate the EN concept into the development of the GI strategy. Therefore, this section addresses the GI approach within spatial planning, namely its definition, principles, mapping method and scales.

2.2.1 Green Infrastructure definition

The Green Infrastructure (GI) strategy (EC, 2013) was simultaneously based on different theoretical and conceptual fields, such as landscape ecology, conservation biology and wildlife protection. Yet trying to combine different disciplines into a new single approach resulted in an "expected inconsistent terminology" (Čivić and Jones-Walters, 2015). Its origins have been widely studied, e.g. Allen (2012), Pankhurst (2012), Mell (2010), Roe and Mell (2013). Despite the various definitions, most come under the umbrella of Benedict and McMahon's (2002) GI definition as "an interconnected network of natural areas and other open spaces that conserve natural ecosystem values and functions, sustain clean air and water, and provide a wide range of benefits to people and wildlife".

The latest definition is "a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings" (EC, 2013).

This synthesises Benedict and McMahon (2002) GI principles[2] in three important aspects: i) the idea of a network of areas, ii) the planning and management of the components, iii) and the concept of ecosystem services (Mubareka et al., 2013; Ahern et al., 2014; Liquete et al., 2015). In addition, Baró et al. (2015), within the OpenNESS project, suggested that GI can be summarised in a three-tiered sense as:

i) A physical entity as a network of ecosystem structures, which are designed and managed to deliver a wide range of ecosystem services (De Groot et al., 2013);
ii) A tool for providing ecological, economic and social benefits through natural solutions;
iii) A strategic approach to enhance natural capital.

However in this thesis, the GI definition adopted is a more pragmatic approach derived from Mell's (2010) and is seen as the connective features (physical and metaphorical) linking different environmental elements across the rural and urban landscape, thus providing multifunctional (ecological, economic and social) benefits for people and wildlife. Within this context, GI is able to act both as a natural resource[3] used as 'sink' (soil, air and water), and as a defined space with primary ecological functions (i.e. a reservoir or forest), whilst being a broader-scale landscape management tool (Mell, 2010).

2.2.2 Key principles of the Green Infrastructure

Multifunctionality and connectivity are the two common elements and functions underlying all GI approaches. These attributes were widely reviewed, e.g. by Tzoulas et al. (2007); Selman (2009); Mell (2010); Mazza et al. (2011); Pankhurst (2012); Madureira (2012); Ahern (2013); Lafortezza et al. (2013); Roe and Mell (2013); EEA (2014); Báro et al. (2015); Liquete et al. (2015).

1) **Multifunctionality** is linked to the provision of a variety of ecosystem services - specifically as an enhancement of mutually beneficial social-ecological interactions by orientating spatial planning towards a means of improving interactions between abiotic, biotic and social systems (Benedict and McMahon, 2002; Roe and Mell, 2013); Multifunctionality refers to the multiple

[2] GI Principles (Benedict and McMahon, 2002): 1) GI networks are identified and planned before development; 2) GI initiatives engage diverse people and organisations, obtaining input from representatives of different professions and sectors; 3) GI plans establish connectivity, for linking natural areas and features and for linking people and programs; 4) GI networks are designed to function at different scales, across political boundaries, and through diverse landscapes; 5) GI planning activities are grounded in sound science and land-use planning theories and practices; 6) GI networks are funded up-front as primary public investments, using the full range of available financing options; 7) GI benefits are afforded to all, to nature and to people; 8) GI is a framework for conservation and development; 9) GI planning respects the needs and desires of landowners and other stakeholders; 10) GI planning takes context into account.

[3] According to the European Union (2015), the natural resources include: 1) Raw materials such as minerals, biomass and biological resources; 2) Energy resources such as hydropower, wind, geothermal, tidal, solar energy and biomass; 3) Air; 4) Water ; 5) Soil; 6) Spatial Resources including (i) type of cover or use (land or in the aquatic environment) and (ii) specific designation of the area (e.g. as a reserve); 7) Biodiversity as the diversity of species within a defined area. It includes i) Within-species abundance relative to a reference year; ii) Conservation status of species; iii) Extent of protected areas for biodiversity and iv) Conservation status of habitats; 8) Other ecosystem resources – the benefits obtained by them as ecosystem services (e.g. the UN's SEEA framework - system of environmental-economic accounting).

functions and benefits that the GI provides simultaneously in the same spatial area (Roe and Mell, 2013), ensured by quantifying and mapping areas which provide a number of ecosystem services (De Groot et al., 2002; 2013). For example, an area suitable for flood protection can likewise serve for recreational needs, the preservation of cultural heritage, natural pasture, and a habitat for wildlife (EC, 2012; Baró et al., 2015). Any ecosystem's functions depend on the biophysical structures and processes, ultimately linked to that ecosystems' condition (as discussed in Maes et al., 2013). Consequently, Liquete et al. (2015) suggest that GI identification should focus only on those services linked to regulation and maintenance, since most provisioning and cultural services do not necessarily enhance natural processes (Maes et al., 2012), and are mainly driven by human inputs like energy or capital. As an example, Liquete et al. (2015) referred to how the presence of food provision in an EEA report on spatial analysis of GI in Europe (EEA, 2014) may highlight the areas of maximum production and will probably spot intensive agriculture that is sustained by human inputs including chemical fertilisers and mechanical means, rather than natural soil organic matter.

2) Structural **Spatial connectivity** addresses the protection of Ecological Networks since all biotic functional groups need core areas to maintain biodiversity (Liquete et al., 2015). It comprises two components: structural connectivity (connectedness) and functional connectivity.

- Structural connectivity is the spatial configuration and condition of the landscape across multiple scales (Andersson and Bodin, 2009). It is the static component of spatial connectivity, measured by landscape structured analysis: shape, size and location of features, including topography, hydrography and human land use/cover patterns, independent of the organisms attributes (Brooks, 2003; EC, 2013);
- Functional connectivity is the dynamic component and reflects how landscapes allow various species to move and expand to new areas (Saura et al., 2014). It combines the effects of landscape structure (habitat patches) and species' behaviour (use and ability) in moving in the landscape (Tischendorf and Fahrig, 2000; Jongman et al., 2004). This connectivity supports genetic diversity, viability and the resilience of habitats and populations (Brooks, 2003) by avoiding fragmentation (Fisher and Lindenmayer, 2007). The widely adopted "patch-matrix-corridor" Forman's (1995) model for broad-scale analyses has been recognised as a simplistic view of spatial connectivity with little ecological support (Boitani et al., 2007).

Hansen and Pauleit (2014) and Lennon et al. (2015) outlined three more principles, addressing governance process:

3) GI as **fundamental infrastructure** – Land should be designed and managed as a multifunctional resource capable of delivering a wide range of environmental and quality of life benefits, including the maintaining and improving ecological functions. Land allocation for development should take into account the valuable physical and biological attributes of the ecological resources (Magalhães et al., 2007) and a strategic approach aiming for long- term benefits but remains flexible for changes over time (Hansen and Pauleit, 2014);

4) The need for **interdisciplinary collaboration** to improve functional synergies in a spatially connected network, and **transdisciplinary** based on knowledge from different disciplines such as landscape ecology, urban and regional planning, and landscape architecture; and developed in partnership with different local authorities and stakeholders.

5) **Social inclusion** - GI stands for communicative and socially inclusive planning and management.

In this sense, GI framework moves beyond traditional site-based approaches of "nature protection and preservation" and towards a more holistic and ecosystemic approach, recognising the complexities of social-ecological interactions. This last approach also includes enhancing, restoring, creating and designing new EN (Lennon et al., 2015; Liquete et al., 2015) towards a "smart conservation" and "nature-based solutions"(NBS) (Balian et al., 2014; EEA, 2015; Potschin et al,. 2016). These approaches address connectivity in the EN by reducing impacts of urban sprawl and fragmentation, and by promoting solutions which increase ecosystem resilience and thereby stabilise the provision of important services, *e.g.* coastal and flood protection, soil fertility, air quality, carbon storage.

2.2.3 Green Infrastructure elements

It is generally accepted that GI includes the following elements (EC, 2010), as identified in Table 2.2.

Table 2.2 Green Infrastructure elements.

GI	Elements
Protected areas	Natura 2000 sites
Healthy ecosystems and areas of high nature value	Floodplain areas, wetlands, coastal areas, natural forests
Natural landscape features	Small watercourses, forest patches, hedgerows (eco-corridors or stepping stones for wildlife)
Restored habitat patches	Areas that can help to expand the size of a protected area, increase foraging areas, breeding or resting for these species and assist in their migration/dispersal
Multifunctional zones	1) Areas, where land uses help maintain or restore healthy biodiverse ecosystems, are favoured over other incompatible activities 2) Areas where measures are implemented to improve the general ecological quality and permeability of the landscape
Artificial features	Eco-ducts or eco-bridges designed to assist species movement across landscape barriers
Urban elements	Green parks, green walls and green roofs, hosting biodiversity and allowing for ecosystems to function and deliver their services by connecting urban, peri-urban and rural areas

According to the GI elements, this infrastructure has some form of coherent EN at its core (Čivić and Jones-Walters, 2015). Currently, EN represents the translation of ecological knowledge relating to fragmentation processes in the Europe landscapes within a GI approach. In this thesis, the GI retains the framework of EN at its core, offering a more sophisticated integration of economic and social factors with the delivery of a range of ecosystem services (Čivić and Jones-Walters, 2015). The focus now, as Čivić and Jones-Walters (2015) mention, should be on “the feasibility of the full translation of the protected area networks into functional ecological networks and on making them essential building blocks of the GI, both at the policy and practice levels”, and should relate to “how to create actual EN at the delivery level”.

2.2.4 Mapping Green Infrastructure

Green Infrastructure is fundamentally a spatial concept (Baró et al., 2015). GI mapping combines geographic information systems (GIS) with modelling techniques based on landscape ecology (Forman and Gordon, 1986) and conservation biology principles (Forman, 1995) via the McHarg approach (1967) of map overlays and suitability analysis (Allen, 2014). However, spatial delineation of GI elements has often been based on a re-classification of available land cover data, combined with information on natural values (*e.g.* Wickham et al., 2010; Mubareka et al., 2013; Liquete et al., 2015).

Lafortezza et al. (2013) describe a conceptual framework for GI mapping with five interlinked components, requiring a systematic assessment and valuation of each framework: ecosystem services (ES), biodiversity, social and territorial cohesion, sustainable development, and human well-being. In contrast (Hansen and Pauleit, 2014) there are other planning frameworks (e.g. Benedict and McMahon 2002; Davies et al. 2006) based on the structuring of the planning processes of case studies rather than on theory. Hansen and Pauleit (2014) outline a framework for assessing multifunctionality in GI planning, based on concepts for ES with a social–ecological perspective. In this study, planning for multifunctionality aims to create synergies that can increase the overall benefit of GI, taking a broad perspective of interrelated social–ecological systems and not only a quantitative sense of ‘‘the more functions the better’’ (Hansen and Pauleit, 2014).

Based on the 2014 EEA report on the spatial analysis of GI in Europe (EEA, 2014), Liquete et al. (2015) present a methodology for mapping GI on the landscape level, based on two points: 1) the delivery of ES, referring to the identification of multifunctional areas with a high or moderate capacity to deliver ES (i.e. a suite of eight ES), and 2) biodiversity conservation and functional connectivity involving habitat suitability mapping for functional groups of interest (e.g. large mammals) with the differentiation between core habitats and migration corridors.

Baró et al. (2015) adapted this methodology, into a proposal of a GI network that identifies potential areas for conservation and for restoration. Also recognized that Liquete et al. (2015) methodology may have some limitations: i) technical infeasibility due to an excessive number of key species or ES; ii) the conservation or restoration GI result neglects the fact that in the case of ES delivery, not all areas need to be of high biodiversity value, iii) the final integration of information requires the establishment of specific thresholds (between data classes) that should depend not only on environmental knowledge but also on policy, socio-economic priorities (Mubareka et al., 2013) and stakeholder involvement (Hansen and Pauleit, 2014).

Another limitation is that the ecological suitability analysis of the landscape is also missing since the ecological assessments are based on the existing land cover and land use classes. In this dissertation, this suitability analysis based on the ecological intrinsic landscape attributes will be highlighted in the proposed methodology for National Ecological Network for Portugal.

2.2.5 Green Infrastructure implementation scales

There is an effort to link and coordinate GI planning and implementation strategies at each scale[4], namely landscape, regional and site along with the urban/rural continuum (Allen, 2014). Mell (2015) summarised GI implementation at three levels: EU and transnational, national, and the sub-national, including regional, municipal and local. At a European scale, within the existing GI macro-scale policy and financial instruments (EC, 2013), there is a developing consensus of the GI delivers. A sustainable solution-based approach to planning and smart long-term strategy policy promoting connective and multifunctional land uses, in a targeted manner to make investment and management GI easier, are central to GI debates (Mell, 2015).

At the national and sub-national scales, due to the variation in government planning structures the development of policy focused on GI, and its subsequent implementation, varies dramatically between nations. Therefore, the GI becomes either embedded or relegated in the legal planning system, reflecting the normative focus of planning in each country and the different opportunities and investment limitations involved in GI development. At regional and local levels, GI implementation has a more visible engagement due to the underlining multifunctionality of green spaces and because of the social benefits and impact it has on local communities (Naumann et al., 2011; Mell, 2015). In addition, there is an evidently increased number of stakeholders, organisations and public agencies involved in implementing GI at this scale (Mell, 2008).

[4] The scales of GI planning (Allen, 2014): Landscape – Network design for species habitat, wildlife corridors; compatible working landscapes; Region – Green space for water quality and supply, greenways for recreation; Site – Low impact development, urban forestry and storm water management.

2.3 | Land morphology

Considering Ecological Networks within the GI strategy, the spatial prioritisation of valuable ecosystems, among other factors, relies on understanding their morphology. Land morphology (LM) constitutes a dynamic and syncretic tool for analysing the trade-offs between ecological functioning and cultural appropriation (Magalhães, 2001), by identifying the ecological potential of the land and the thresholds of landscape resilience (Magalhães et al., 2007). Therefore, in this dissertation, LM is considered an essential tool for modelling natural systems and an important ecological input for ecological network delimitation (chapter 3) and flood risk mapping (chapter 5). In chapter 4 a detailed analysis of the LM concept is presented (in line with Magalhães, 2001; Magalhães et al., 2007), along with a literature review on landform classification methods as well as the development of the LM mapping method, applied at the national level. For this reason, this section only summarises the different terms and definitions on this subject and the origins of landform classification.

2.3.1 Land morphology terms and definitions

Despite their widespread usage, there are no unique or universal terms for terrain, topography, relief, landform, land surface form or land morphology. They mean different things to different specialists.

1) The word "terrain" is normally used as a general term in physical geography, referring to land relief as the vertical and horizontal dimension of the land surface (Collins English Dictionary, 2015). Mitchell (1991) described it as the expression of the geological character, the soil and the surface geometry of the Earth's crust. Thus, it is a facet of land with more or less homogeneous properties, usually expressed in terms of slope morphology, soil characteristics, drainage condition, vegetation cover and other natural features (Prasad and Mahto, 2009). In addition, terrain, derived from the Latin word *terrēnum* "land, ground" can be translated as "of earth, earthly, land" and literally "dry land" as opposed to "sea" (online Etymology Dictionary, 2015), and also an extent of ground, region, territory associated with natural features and military potential or socio-economic aspects (Collins English Dictionary, 2015);

2) "Topography" is the study or detailed description of terrain (Collins English Dictionary, 2015). From the Greek words τόπος (topos, "place") and -γραφία (-graphia, "writing") it is a description of the place (Etymology Dictionary, 2015) or "local history". Although in a narrow sense, this word is often used as a synonym for relief itself, referring to the differences in elevation or slope gradient of the area on a broad scale (FAO, 1998).

3) "Relief" can be defined as the set of forms that shape the surface of the earth crust and is essential to understanding the topography of an area. It can be divided into three orders concerning

the origin of the geological processes (endogenic and exogenic) and the scale: 1st order - major structural strutures of the earth's surface – Continents, orogenic belts, oceans, 2nd order results from the tectonic action over the continents - wrinkled structures (anticlinal, sinclinal and monoclinal), surface fractures and faults, etc.; and 3rd order results from the action of the erosive processes on the forms of 2nd order relief - plains, valleys, hills and mountains, etc. In Anglophone regions e.g., Great Britain, North America, relief is usually prefixed by relative or local. It defines the maximum elevation of a particular area above sea level. It is synonymous with topography where "low" and "high" relief indicates a relatively flat area and a mountainous region respectively. Dietrich et al. (2003) defined local relief as the height difference between a valley bottom and adjacent hilltop.

4) "Land" refers to the Earth's surface not covered by water (Oxford Dictionary, 2015). According to FAO (1998), land comprises the physical environment including climate, relief, soils, hydrology and vegetation, to the extent that these influence the potential for anthropogenic land use. Land, according to von Humboldt (1769–1859), is synonymous to landscape in its meaning, as the total character of a part of the Earth's surface or the tangible ecosystems, including all biotic and abiotic aspects (Zonneveld, 1989).

5) "Landscape" is a part of the space on the Earth's surface consisting of a complex of systems, formed by geological activity, water, air, plants, animals and Man and that by its physiognomy forms a recognisable entity (Zonneveld, 1989). Cabral's definition of landscape in 1973, as the figuration of the biosphere, results from the complex interaction between human and all living things - plants and animals - in balance with the physical factors (Cabral, 1980). Magalhães (2007) adds to this stating that it is figuration of the ecosphere involving human action.

6) "Landform" is considered to be a natural feature of the land surface (Macmillan Dictionary, 2015). This term was first used in 1931 by the Hungarian-born American cartographer Erwin Raisz, the author of "General Cartography" (Robinson, 1970). Landforms have been defined by several authors, such as Hammond (1964), Dalrymple et al. (1968), Peucker and Douglas (1975), Speight (1977), Whittow (1984), Pennock et al. (1987), Dikau (1989). Among others, Hammond´s (1965) landform definition has a subjective semantic meaning which is "a terrain unit created by natural processes in such a way that it may be recognised and described in terms of typical attributes where ever it may occur". Landforms are a configuration of the land surface taking distinctive forms and produced by natural processes. Evans (2012) defined them as areal objects on a Digital Elevation Model (DEM) with a third dimension, meaning they are volumetric.

7) "Land surface form" or "land morphology", in Portuguese "morfologia do terreno", is a term that became widely known through the morphometric work of Hammond (1964) to indicate the

principal object of Geomorphometry (Pike et al., 2009). The land surface form is considered a three-dimensional geometry to which some consideration of surface material is usually added (Hammond, 1965) and is characterised by a complex structure of nested hierarchies (Dikau, 1991; Magalhães, 2001). Minár and Evans' (2008) definition of land surface form considers a three level hierarchy: The first level - landform elements[5] (elementary form) represent the smallest and simplest units characterized by geometric simplicity, *e.g.* linear slope, curved slope or horizontal plain; the second level – landforms are composite forms, are single elementary forms but most consist of several elementary forms, e.g. valley, terrace; the third level - land system[6], defined by a recurrent pattern of landforms, frequently correspond to ecological land properties such as soil, climate and vegetation (Speight, 1977; MacMillan et al., 2004).

In this thesis, land morphology (LM) is considered to be the form of the Earth's surface, a three-dimensional geometry, characterised by a complex structure of nested hierarchies (Sauer, 1925; Dikau et al., 1995). The LM concept (LMC) defined by Magalhães (2001) is used to define the landscape form that arises from its dominant physical structures. For any given scale, the LM can be systematised into landforms. The latter are functionally interrelated parts of the land surface (Pike et al., 2009) taking distinctive forms and produced by natural processes as a result of the cumulative influence of geomorphological, geological, hydrological, ecological and soil forming processes over time (MacMillan and Shary, 2009).

The Land Morphology concept (LMC) provides a means to classify the wet and dry systems in the hillslope profile and supports an understanding of ecological functioning by classifying landforms according to their hydrological position. It is, therefore, a helpful assessment tool to inform EN delimitation, namely the water subsystem, and flood risk mapping.

2.3.2 Origins of landform classifications

Landscape classification into landforms was first developed in the 19th century. However, automatic landform classifications emerge only after the first Digital Elevation Model by Miller and Laflamme in 1958 (Pike et al., 2009). As landforms are defined as homogeneous parts of the Earth's surface, in terms of land surface parameters such as slope gradient, elevation and curvature, it became possible to map them through Geographic Information Systems (GIS). These landforms classifications will be explained in chapter 4 as will the development of an LM mapping method. There will also be a

[5] Other synonymous terms: Landform element (Speight 1977, Bolongaro-Crevenna et al., 2005; Hugget, 2011), landform unit (Schmidt and Hewitt, 2004), surface patches (Peucker and Douglas, 1975), relief unit, landscape type (Romstad, 2001), land element (Schmidt and Hewitt 2004), land component (Speight, 1977), morphometric features (Wood, 1996, 2009), landscape element or land unit (Zonneveld, 1989), landscape facet (Burrough et al., 2000; FAO, 2007) and landform facet (MacMillan et al., 2004).

[6] Other synonyms: Land unit (FAO, 2007), soil-landscape unit (Jenny, 1941; de Bruin and Stein, 1998; Drăguţ and Blasche, 2006; Wysocki et al., 2011), ecological units (Cleland et al., 1997), topo-climatic classes (Burrough et al., 2000).

comparison between the two different automatic landform classifications: the Topographic Position Index (TPI) method (Weiss, 2001; Jenness, 2006) and Missouri Resource Assessment Partnership (MoRAP's) landforms that used Hammond's method based only on a slope and local relief landforms (True, 2002).

Therefore, in this section, the first examples of landform classifications started in the 19th century are summarised (Table 2.3).

Table 2.3 Origins of landform classifications

Authors	Variables	Description
Brisson (1808)	Ridges and Valleys	Conceptualisation of topographic ridges and valleys
Saint-Venant (1852)	Ridges and Valleys	The first explicit definition of ridges and valleys as points of minimum slope
Gauss (1827)	Curvature	"General Investigations of Curved Surfaces"
Gilbert (1909, 1928)	Convexity	"Convexity of hilltops"
Cayley (1859)	Contour and slope lines	"On contour and slope lines" - first definition of elements of physical geography: summit (hill), immit (depression) and "knot" (point of minimum elevation on the ridge line that determines the watershed that runs from summit to summit), ridge line or "ligne de faîte" and "course line" as "ligne de thalweg"
Maxwell (1870)	Regions of elevation	"On hills and dales" - defined the boundaries of "hills" (summit or tops) and "dales" (basins or valley) and deduced a mathematical relationship between singular points of "terrain skeleton" – on any given surface the number of summits equals the number of saddles plus one.
Cayley and Maxwell (1870)	Surface networks	"Theory of Surface Networks" -"every summit has a saddle". Termed the six surfaces or landform elements: Summit (hill), Saddle, Pit (Immit – Depression, Bottom), Ridge (Divide), Channel (Thalweg, valley) and Slope (Plane, Flat).
Folque (1865)	"Geographic map of Portugal"	Relief representation through contour lines technique
Gomes (1875)	"Orographic and regional map of Portugal"	The country division into several regions according to natural features highlighting the relief main lines.
Choffat (1907)	"Hypsometric map of Portugal	Elevation together with contour lines.
Raisz (1931)	"Physiographic map of landforms of the United States"	Identification of landform types: Plains (sand and gravel, semi-arid, grassland, savannah, forest, needle forest, forest swamp, swamp, tidal marsh, cultivated land), coastal plain, flood plain, alluvial fans, conoplain, cuesta land, plateau (subdued, young, dissected), folded mountains, dome mountains, block mountains, complex mountains (high, glaciated, medium, low, rejuvenated), peneplain, lava plateau (young, dissected), volcanoes, limestone region (with sinkholes, dissected, karst, tropical), coral reefs, sand dunes, desert of gravel, deflated stone surfaces (hamada), clay, loess region, glacial moraine, kames, drumlin region, fjords, glaciers, shoreline (sand, gravel, cliffed), and elevated shorelines and terraces.

2.4 | References

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5| http://www.cbd.int/cop10/doc/
6| http://ec.europa.eu/environment/nature/biodiversity/policy/index_en.htm
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3 | THE NATIONAL ECOLOGICAL NETWORK: A MAPPING PROPOSAL TO PORTUGAL

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3 | THE NATIONAL ECOLOGICAL NETWORK: A MAPPING PROPOSAL TO PORTUGAL

Abstract

The Ecological Network (EN) is a spatial strategically connected infrastructure of abiotic and biotic systems, underlying the provision of (multi) functions valuable to society and nature. In Portugal, there is no EN map at the national level and the regional and municipal levels have no defined EN criteria.

This paper presents a methodology for mapping the national EN (NEN) for mainland Portugal based on multi-level physical and biological evaluation criteria. The NEN components were studied independently and collectively, derived from a high spatial resolution dataset. The selected NEN components represent the highly valuable ecosystems and the most sensitive areas. The results show that most of the ecological components do not overlap. The NEN1 has high biodiversity and ecosystem stability, which equally means they are more vulnerable to anthropogenic activity. NEN1 covers a total of 67 % of mainland, yet as of 2017, only 25 % is legally protected in nature conservation areas. Priority must be given to NEN1 in order to avoid/decrease landscape fragmentation, environmental risks and natural disaster prevention.

This NEN mapping proposal emphasises the quality or potential of physical components in its biological driven base, allowing the articulation with the nature conservation and at-risk areas. It can be used to represent an effective planning tool to counteract fragmentation and a political instrument to take decisions based on a more thorough analysis of the land value and its functions. It represents the first attempt to map Portuguese EN and is available online at http://epic-webgis-portugal.isa.ulisboa.pt/

Research highlights

•EN is a planning tool and a spatial framework that promotes biophysical connectivity.
•The landscape scale analysis is used to map Portuguese National EN (NEN).
•NEN classification is used to indicate areas with highly valuable ecosystems.
•Existing protected areas are insufficient to ensure landscape ecological balance.
•Results accuracy allows their transfer to regional and municipal scales.

Keywords •Ecological Network •EN methodology •Biophysical analysis criteria •Ecological value •GIS Mapping •National scale.

3.1 | Introduction

The multiple changes in landscape transformation and fragmentation (Tillmann, 2005; Hagen et al., 2012) are linked to population density and growth, land abandonment, urbanisation and consumption patterns (Jaeger et al., 2011; Jongman and Pungetti, 2004; Lafortezza et al., 2013). The result is a reduction in biodiversity and the decline of ecosystem quality (Mücher et al., 2010). In what concerns Natura 2000, approximately 82 % of EU territory falls outside these areas (EC/CIRCABC, 2012) and it has become undeniably accepted that protected areas alone will not provide long-term protection of biodiversity. From the concept of the 19th century green corridors to greenways (Linehan et al., 1995; Ahern, 1995; Fabos, 2004) and the post-modern concept of landscape multifunctionality (McHarg, 1992; Selman, 2009) as promoted by the European Landscape Convention in 2000 (Council of Europe, 2000), the focus on the need to establish ecological networks (EN) and ecological connectivity (Goodwin, 2003) have become widely recognised.

Consequently, under the EN concept (ECNC, 2010) and the recent EU Biodiversity Conservation Strategy (EC, 2011), the concept of landscape is regarded as a multifunctional dynamic resource, to which a wide range of ecosystem services are associated (EEA, 2015). The first and most common EN definitions were based on hubs and links (Benedict and McMahon, 2002), core areas, buffer zones and corridors (Bennett and Wit, 2001). They were originally planned to favour overall biodiversity conservation but in practice, the focus is on the needs of species whose habitat is assumed to be on a landscape scale (Mell, 2010; Čivić and Jones-Walters, 2015). Within the Green Infrastructure (GI) framework (EC, 2013), the EN represents an effective political instrument and planning tool to counteract fragmentation (Fischer and Lindenmayer, 2007) by (i) maintaining and establishing ecological connectivity with different land uses (Magalhães et al., 2007; Čivić and Jones-Walters, 2015), (ii) ensuring the ecological coherence of the Natura 2000 Network, in order to maintain and improve ecosystem services (Lafortezza et al., 2013; Kopperoinen et al., 2014, Maes et al., 2015), (iii) conserving and buffering core areas in terms of its natural/semi-natural value. The EN concept assumes a holistic view of land-use planning and biodiversity conservation. The Abiotic, Biotic and Cultural (ABC) resource model (Ahern, 1995; Ahern, 2007) and the Landscape-System methodology (Magalhães et al., 2007, 2013) are examples of inclusive models or multi-objective tools that recognise the needs and mutual impacts of humans on biotic and abiotic systems and processes.

In this work, the EN is considered to be a spatial concept based and a planned network, designed and managed for various purposes, recognised as a system of landscape structures or ecosystems (Forman, 1995; Magalhães, 2001; Franco, 2004) that concerns the vertical and horizontal connection of biophysical systems (Jongman, 1995; Jongman and Pungetti, 2004). It provides the physical conditions that are necessary for maintaining or restoring ecological functions such as nutrients cycling, soil development or water management (Franco, 2004; Boitani et al., 2007; Magalhães et al., 2007), supporting biological and landscape biodiversity and promoting the sustainable use of natural resources (Forman, 1995; Bennett and Wit, 2001; Bennett, 2010). Mapping the EN is not just the mapping of key habitats but how they are connected including all landscape elements (Firehock, 2015). In summary, EN is a spatial framework, considered a fundamental strategically connected infrastructure of abiotic and biotic systems, underlying the provision of (multi) functions valuable to society and nature.

The main goal of this work is to describe a methodology to map the National Ecological Network (NEN) for mainland Portugal and construct the key guidelines for its implementation, referring to the environmental services benefits, according to ecological functions, value or sensitivity and suitability. Specifically, it represents the first attempt to map Portuguese EN as a single entity based on a DTM of 25 m spatial resolution. A subsidiary aim is to ensure that all maps resulting from this initiative are available online and free for download.

This study represents an important contribution to science because in Portugal the EN was only incorporated into its legal system in 1999 and some gaps in the Portuguese legal system remain. These include inconsistent criteria to map EN at all planning levels, unclear legally bounded to other planning instruments. Simultaneously, there is a lack of available maps at a national scale, regional and municipal maps, although in existence, with inconsistent EN delimitations and criteria. Therefore, this work can be seen as the building block for landscape planning and management instruments at the national, regional and municipal levels. It may also be used to integrate the Portuguese environmental policies more effectively, namely the Fundamental Network of Nature Conservation (RFCN) comprising the National Ecological Reserve (REN), National Agricultural Reserve (RAN) and Public Hydric Domain (DPH) and Nature Conservation Areas (NSCA). At the international level, this EN map and data may also be used to integrate the EU Biodiversity strategy (EC, 2011) need of a set of biophysical maps of ecosystem services (Action 5) and into the upcoming GI framework (EC, 2013) which is to be implemented between 2014 and 2020.

3.2 | Portuguese context

In Portugal, the EN concept was included in the legal system in 1999, under Decree-Law nº 380/99 (Territorial management instruments legal regime), as an instrument for planning and management of the landscape at all scales, including national, regional municipal and local levels. In the latest DL nº 80/2015, the EN was defined by areas, values and key systems for environmental protection and enhancement of urban and rural areas, including the natural at-risk or vulnerable areas. The at-risk areas are comprised in another planning instrument, the National Ecological Reserve (REN). The REN was created in 1983 under DL nº 321/83, last modified by DL nº 239/2012, and is a legal framework that integrates all areas requiring special protection due to their ecological sensitivity or exposure, and vulnerability to natural hazards. This includes coastal and river areas, aquifer recharge areas and steep-slope areas for erosion protection. In addition, there is the Public Hydric Domain (DPH) defined under the Royal Decree of 21st July 1884 and modified by later DL nº 468/71, the National Agricultural Reserve (RAN) under DL nº 451/82, modified by DL nº 73/2009, two legal frameworks that aims to protect water and soil resources, respectively.

Faced this, it was created the Fundamental Network of Nature Conservation (RFCN) under DL nº 142/2008, as framework that attempts to organise and integrate those planning instruments into a network of conservation areas that consists of (i) core areas that comprise National System of Classified Areas (NSCA), Natura 2000, Important Birds Areas (IBAs), Ramsar sites, Biosphere and Biogenetic reserves and classified geosites; and (ii) ecological corridors or continuity areas including the REN, RAN and DPH areas. The RFCN is thus rather simplistic since it is focus only on areas of biological interest and is just an overlaid of the legal core areas without any consistent map of the continuity areas at the national level, defined and managed at different scales.

Concerning the EN delimitation in territorial management instruments (see supplementary material Table S.1), in these plans, the national level (National Programme for Land Planning Policy - PNPOT) does not include any EN delimitation while the regional plans (PROT) establish the Regional Ecological Network, referred to as Regional Structure Plan for Environmental Protection and Enhancement (ERPVA). At the municipal scale (Municipal land management plans - PMOT), the EN is not a distinct class of the municipal plans. In particular, in the rural land includes the RFCN areas and other natural at-risk areas and within urban perimeters, the municipal EN entitled urban EN, comprise of public or private areas deemed necessary for environmental balance and for the protection and enhancement of landscape and natural heritage.

In this context, some gaps in the Portuguese legal system have been identified (i) Portuguese legislation still does not consider EN a unique entity, having different names according to scale; (ii) the EN criteria are not defined for all planning scales, and therefore, different definitions and detailed representations, even on the same scale, emerge; (iii) at the national level, the PNPOT does not include any EN maps, whilst the regional and municipal maps have different delimitations and criteria. There is no national mandatory instrument referring to the EN; (iv) the RFCN gives particular relevance to nature conservation and at-risk areas, however the continuity areas of the RFCN are not mapped at national or regional scales and do not have well-defined criteria. For instance, in soil protection law (RAN), soils within urban areas are excluded from this protection, thus compromising urban and peri-urban area sustainability.

Despite being included only in the Portuguese legislation in 1999, the EN concept (Magalhães, 1993) was used for the first time in the Plano Verde de Lisboa in 1992-93 (Lisbon Green Plan) (Telles, 1997). Subsequently, EN maps were systematically applied elsewhere in Portugal at the municipal (Magalhães et al., 2004, 2007, 2012) and regional scales (Magalhães et al., 2003; Franco et al., 2013) developed under the Landscape-System methodology (Magalhães et al., 2007).

3.2.1 Study area

Mainland Portugal covers an area of 92.212 km² and 10.6 million inhabitants, with two metropolitan areas, Lisbon and Porto, hold 43 % of the total population (INE, 2013). Essentially, due to a Mediterranean climate and heterogeneity in terms of geology, soil, land morphology and vegetation, the Portuguese landscape is characterised by (i) enclosed valleys bottoms with abrupt and extensive hillslopes on hard lithology located in the North, e.g. mountainous reliefs in Minho region, Douro valley, Serra da Estrela; (ii) a gently waved relief landscape that shows peneplain characteristics in the South of the Tagus river, e.g. Alentejo peneplain (Feio and Daveau, 2004), constituted of clay soils with oak trees (*Quercus suber* and *Quercus rotundifolia*), and by several river terraces such as the sedimentary Tagus and Sado basins; and (iii) a coastline with 976 km length from Minho River mouth in the northwest, to Guadiana River mouth in the Southeast, constituted by an alternation of cliffs and capes, with large sections of beaches.

Relative to nature conservation areas in Portugal, the Fundamental Network of Nature Conservation (RFCN), as mentioned, is an attempt to integrate those areas defined in several legal instruments. Figure 3.1 illustrates the available nature conservation areas mapped for Portugal, both nationally and internationally. This map derived from ICNF data (2013) and compiled by Leitão *et al.* (2013b). As demonstrated in Figure 3.1, it includes only the core areas of the RFCN since the continuity areas (REN, RAN and DPH areas), are not all defined and mapped for the country. Therefore, RFCN map consists of (i) 2 070 429 ha of Natura 2000 with 60 Special Areas of Conservation (SACs) and 40 Special Protection Areas (SPAs) mainly located in wetlands, mountainous and coastal areas, (ii) 54 Important Birds Areas (IBAs) with an area of 1 470 650 ha, where 67 % of these areas corresponds to SPAs (90% of SPAs overlap IBAs area since most of SPA eventually originated them) (iii) 18 Ramsar Sites are registered with a total area of 117 689 ha, which corresponds to 1 % of the Portugal area (iv) 3 Biosphere reserve and 8 Biogenetic reserves (v) 49 designated National System of Classified Areas (NSCA) corresponding to 757 024 ha, and classified geosites (Brilha et al., 2013).

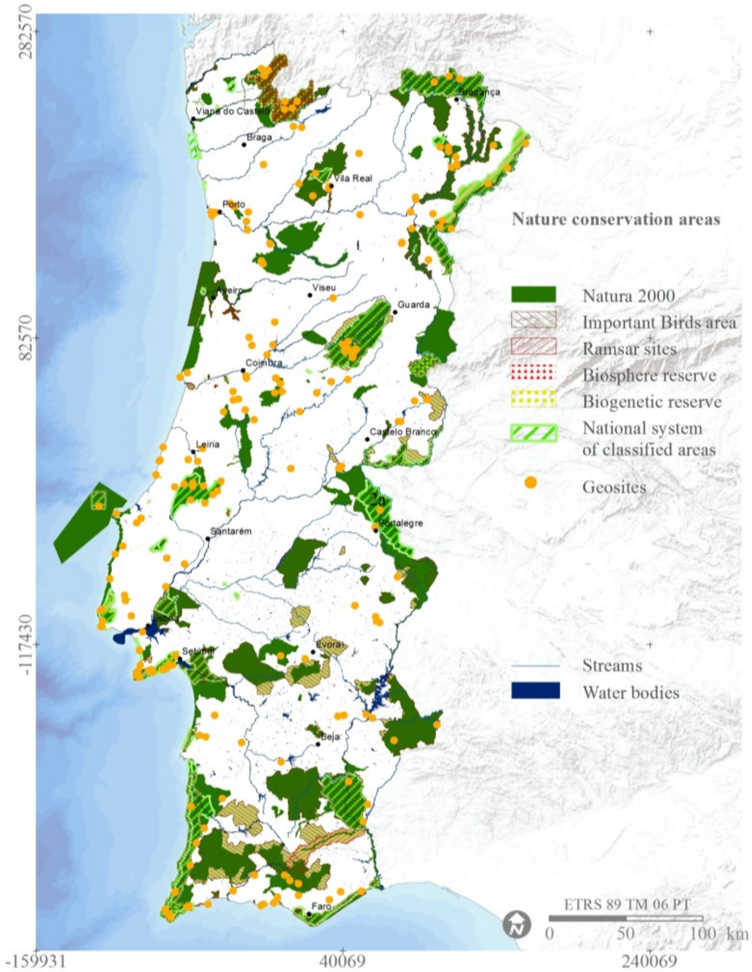

Figure 3.1 Map of Nature conservation areas for Portugal (compiled by Leitão *et al.*, 2013b)

This map identifies the areas where the resources exploitation should be limited, because of their recognized natural, ecological and/or cultural values, essential for biodiversity conservation, natural habitat and species protection. Those areas were biological based mapped overlooking the key physical components of the landscape and its ecological continuity. Simultaneously, the lack of available data for the continuity areas mapped for Portugal highlight the discontinuity character of these areas. Additionally, although all the data came from legal sources there are some discrepancies between their limits.

Furthermore, demographic changes in Portugal, such as an aging population, decreasing of the resident population in 10.5 million to 8.9 m in 2053 (INE, 2013) alert us to the need for national and regional planning policies to avoid the urban sprawl of existing cities, giving preference to urban rehabilitation and creating conditions/ incentives for social and economic development of rural areas. Due to this, mapping the EN components for Portugal, based on physical and biological systems, as geology, soil, land morphology and vegetation, besides the nature conservation areas, is essential for an effective planning framework of existing and potential ecological areas.

3.3 | Method

This paper presents a methodology for mapping the EN for mainland Portugal, based on the Landscape-System methodology (Magalhães et al., 2007), and defined as a multi-level ecological evaluation criteria which integrate, in a single framework, the physical and biological systems. The physical system includes geology/geomorphology, land morphology, soil, water and climate components, whilst the biological system comprises habitat and vegetation, and the interactions between them. The mapping of these two systems promotes a more holistic and adaptable approach to landscape management. This provides, in turn, a theoretical knowledge of ecological systems, and spatial delineation of EN components, in order to achieve a spatial framework that defines areas of existing and potential ecological connectivity at the national level.

These systems were studied independently and collectively at the national scale. The innovation relies on the implementation, at the national level, of the EN method and simultaneously the specific mapping methods to assess the National EN (NEN) components.

3.3.1 Data collection

The NEN methodology was implemented through a GIS using Argis10.0 Esri® software, based on a 25 meter spatial resolution digital terrain model (DTM) for mainland Portugal. It was collected and assessed the available background information including data on water, land morphology, soil, geology/geomorphology, and nature conservation areas (detailed in supplementary material TableS3.2). The biggest challenge was to overcome missing data since there was many spatial gaps and no unified maps for the whole country, e.g. soil map.

3.3.2 Implementation of the method

A GIS-based integrated model is used to implement the methodology for EN mapping at the national scale. The landscape scale analysis is used for identifying, mapping and prioritising essential areas. As shown in Figure 3.2, the NEN methodology developed is structured as follows: (i) compilation of existing data; (ii) map layer creation via data acquisition and producing georeferenced cartography for the subsystems, e.g. soil, geology maps; (iii) analysing and assessing data individually through spatial modelling; (iv) overlaying data into two levels using spatial analysis.

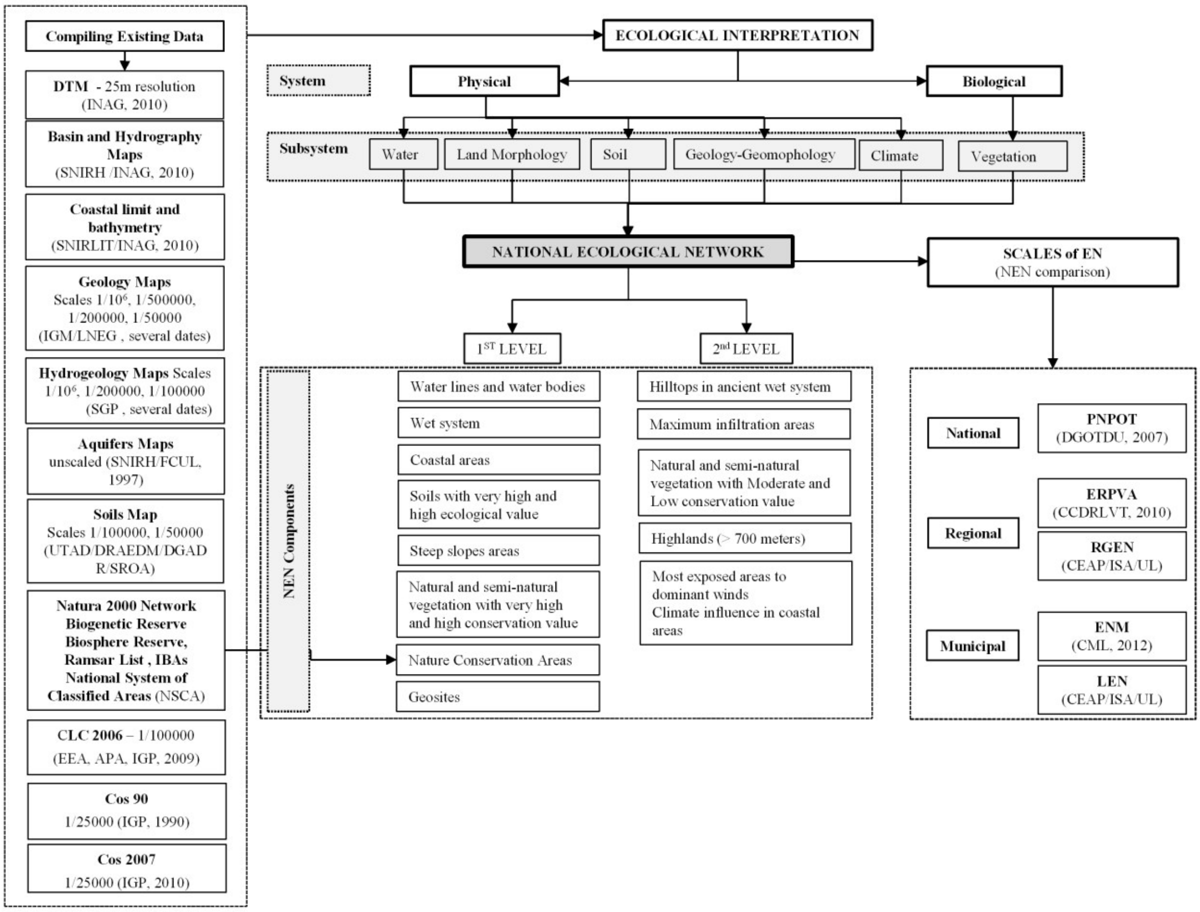

Figure 3.2 Methodology for NEN mapping

The NEN is hierarchised in two levels according to the ecological value or sensitivity, and function of each component. Ecological sensitivity can be defined as (a) areas that contribute to biodiversity and ecosystem stability, often through coupling relationships between its components and ecological processes (Liang and Li, 2012); (b) areas containing very vulnerable natural habitats with a high degree of risk of losing their integrity/identity, justifying the need for special preservation measures (Rossi et al., 2008); and (c) areas with a high probability of ecological/environmental problems as a result of human interference or natural environmental changes (Liang and Li, 2012).

The first level of NEN (NEN1) presented has a higher value than the second (NEN2) and consequently justifies special preservation and recovery measures. The first level indicates the areas that should be protected in NEN, in addition to nature conservation areas, showing the importance of protecting these ecosystems as core areas of the EN. That is to say, these first level components comprehend areas of high biological sensitivity and productivity, with higher importance in nutrient storage and distribution, soil protection and flood prevention, pollutants filtering and sheltering species, essential for climate and water cycle regulation. A definition for each NEN1 and NEN2 ecological component and the environmental services associated is presented in the supplementary material Table S3.3.

As the method is made up of a sequence of analysis and evaluations of several indices/models for each EN component that are driven by a GIS model, these were assigned with a GIS code for each. Relatively to climate component, the difference between the spatial resolution of the climatic analysis (9 x 9 km) and the DTM (25 x 25 m) used, does not allow a direct transposition of the data calculated into the NEN map, namely the temperature and wind speed areas, in order to identify the most exposed areas to dominant wind.

3.3.3 Study innovation and importance

As aforementioned, this work represents the first attempt to map Portuguese EN as a planned structure rooted in physical and biological components at the national level. The innovation of this study is in regards to the selection/identification of the NEN physical and biological components and the specific mapping methods to assess them and their integration.

A significant contribution was the production of new maps to overcome missing data, namely a unified soil map for the whole country, a land morphology map comprising all the river ecosystems and floodplains for mainland Portugal (Cunha et al., 2017). Simultaneously, the NEN components were assessed individually for the first time, according to ecological value, revealing specific ecological functions, directly influenced by hydrologic availability, soil genesis processes and fertility, plant biodiversity (species) and habitat resources.

Furthermore, the NEN criteria and maps presented, derived from a high spatial resolution dataset, provide a network that can be replicable, with necessary scale adjustments, at all planning scales. Therefore, such maps represent an effective planning tool and important political instrument for public institutions at regional and municipal levels. As landscape organisation should be based on multiple land use according to their ecological suitability, this newly created EN map is very important for land valuations and can support both insurance companies and private owners in their operations, legal challenges and estimations. It can help the government and environmental authorities to take decisions, based on a more thorough analysis of the land and its functions. This improves the management of natural risk protection and resilience building, whilst also enhancing landscape aesthetics and an appreciation of Portuguese natural heritage.

3.4 | Results and discussion

As aforementioned, the NEN classification is used to indicate which areas are highly valuable ecosystems, e.g. significant soil fertility and productivity, natural vegetation of high conservation, etc. In the previous section 3.3.2, the methodology was described, specifically how the two NEN levels were created via the selection of NEN components, e.g. water bodies, wet system, soils of very high and high ecological value, etc. (Table S3.3). The NEN1 has the greatest ecological sensitivity due to high biodiversity and ecosystem stability, which equally means they are more vulnerable to anthropogenic activity. NEN1 covers a total of 67 % of mainland Portugal, yet as of 2016 only 25 % is legally protected in nature conservation areas. NEN2 correspond to less sensitive areas and include maximum infiltration areas, highlands and vegetation with a lower environmental conservation value. It represents 55 % of Portugal´s mainland area.

In total, 87 % of mainland Portugal would come under either NEN1 or NEN2 designation, if the recommendations presented in this study are considered and enacted by the Portuguese state territory authority (Direcção Geral do Território). Approximately 35 % of mainland Portugal comes under both NEN1 and NEN2. Priority must be given to NEN1. NEN1 areas should receive full protection from the Government in order to avoid/decrease landscape fragmentation, environmental risks and natural disaster prevention. There may be some concessions for NEN2 area development but any activity should be monitored and require specific licensing. In the following sections and Figures 3 to 8 break down each level and the combined level in turn.

The areas that do not come under any designation represent zones of poor soil fertility and limited ecological value. Typically they include grasslands, shrubs and are not suitable for agricultural purposes. Some of them might be, if accessible, good options for urban development.

3.4.1 NEN1

It is important to emphasise that this NEN implementation calls for integrated management that looks at interdependent factors and does not just protect individual elements. Moreover, it will be also an important planning tool to complete the functionality of the network of protected areas, connecting them into a complete system with natural areas. According to NEN1 map (Figure 3.3) the results for the individual components are presented as follows (details shown by the numbers):

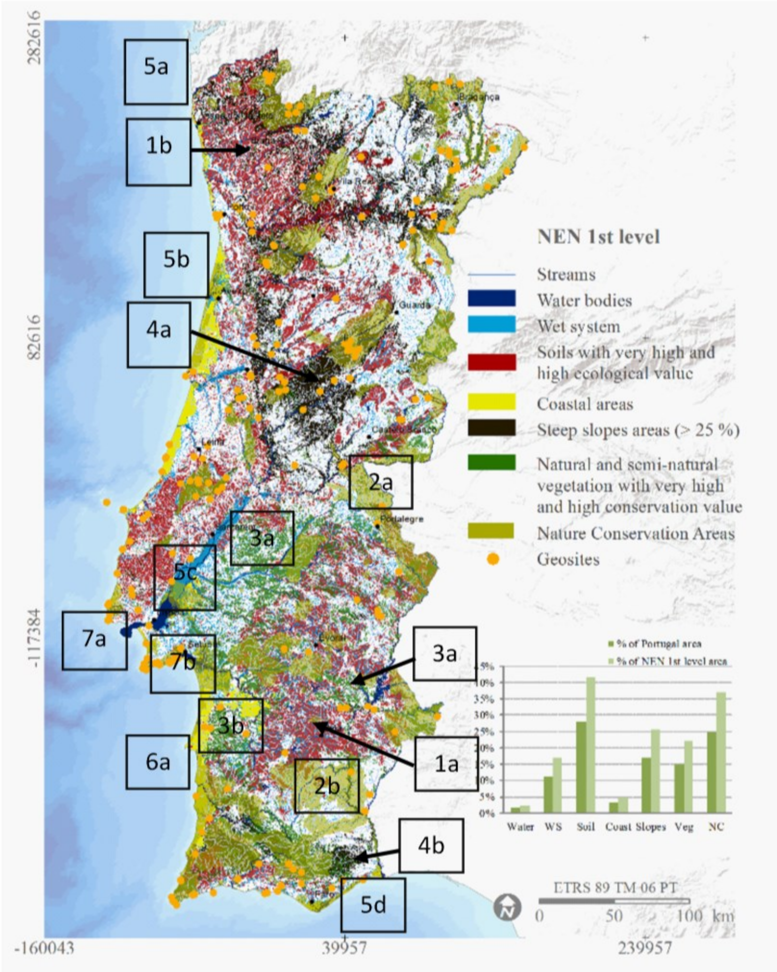

Figure 3.3 Map of NEN1 individual components (details shown by the numbers)

(1) Soils of very high and high ecological value (SHVE) are the largest area of NEN with 2 486 642 ha.

- 8 % of the area is located on steep slopes. As slopes are not known for their high-quality soils, these areas need to be investigated further as it may indicate an error in soil mapping due to lack of accuracy and small scale mapping;

- Particularly productive area with clay soils is located in Alentejo, south Portugal **(**Figure 3.3 and Figure 3.4 detail 1a);

- High productive valley bottoms enclosed by steep slopes in the mountainous highland North (Figure 3.3 detail 1b)

- According to current legal status, only 20 % of this area comes under nature conservation and all the soils in 1a and 1b could be incorporated into existing national agricultural reserve (RAN).

- At the moment the soil protection law (RAN) doesn't work:

i) The soils are mapped at the municipal level based on outdated soil map with missing data for many locations;

ii) The soil classification are different along the country resulting in different evaluations, most based on land use rather than its potential;

iii) The soils within urban areas are excluded from this protection, thus compromising urban and peri-urban area sustainability.

- Certainly, this area needs to be studied alongside municipal soil maps for validation and improving mapping purposes.

(2) These areas are currently legally protected nature conservation areas (Figure 3.1) corresponding to 2 197 499 ha (25 % of Portugal area).

- Of these areas, 70 % of the nature conservation areas (1 538 250 ha) protect another NEN1 component. This corresponds to 17 % of NEN1 is currently legally protected.

- However, 659 250 ha of nature conservation areas protect only the biological system namely it is an important IBAs area (birds) in S. Mamede Sierra (Figure 3.4 detail 2a).

(3) There is an important area of biological diversity and 761 345 ha of the natural and semi-natural vegetation with high conservation value (50 % of the area) is not currently protected.

- Montado in the south of Tagus River is particularly adapted to extreme conditions of climate, soil and water availability mostly to oak forests (Quercus suber and Quercus rotundifolia) in southern Portugal (3a).

- Near the Natural Park of Costa Vicentina in the coastal Alentejo area could be expanded to incorporate the natural and semi-natural vegetation (Figure 3.4 detail 3b).

(4) Steep slopes correspond to 1 522 690 ha (17 % of Portugal´s area) and are highly susceptibility soil erosion areas, mostly located on hills or hillsides of narrow valleys, especially in hard lithology.

- 16 % of these areas are protected with existing natural or semi-natural vegetation, which reveals that the soil in these situations is correctly covered with adequate vegetation – decrease soil erosion

- Attention should be given to Sierras Estrela (detail 4a) and Algarve (4b) at a local scale, namely in the current legislation that maps all of the at-risk areas (in the national ecological reserve).

- The soil erosion risk is enhanced by incorrect land use practice and incorrect soil cover, and also forest fires in the summer, mostly in pines and eucalyptus areas.

(5) The wet system includes valley bottoms, floodplains and wetlands, corresponds to 1 005 965 ha and represents 11 % of the country´s area.

- 55 % of the area is coincident with soils of high ecological value, namely Fluvisols and Colluvisols and should be protected and building restricted. These areas have high economic value because there are very fertile.

- 23 % of the area of the wet system is classified as nature conservation area, namely wetlands in the Minho and Lima rivers (5a), Ria de Aveiro (5b), Tagus Lezíria (alluvial agricultural field) floodplain (Figure 3.4 detail 5c), Faro and Vila Real de Santo António Campina (farming land) (5d).

- These areas include floodplains as flat and concave areas contiguous to streams in which slope is less than 5 %, along all over the drainage network of the watershed. This can be used as the preliminary delimitation of floodplains and potential flood risk areas in basins where there is no available hydrological data (Cunha et al 2017).

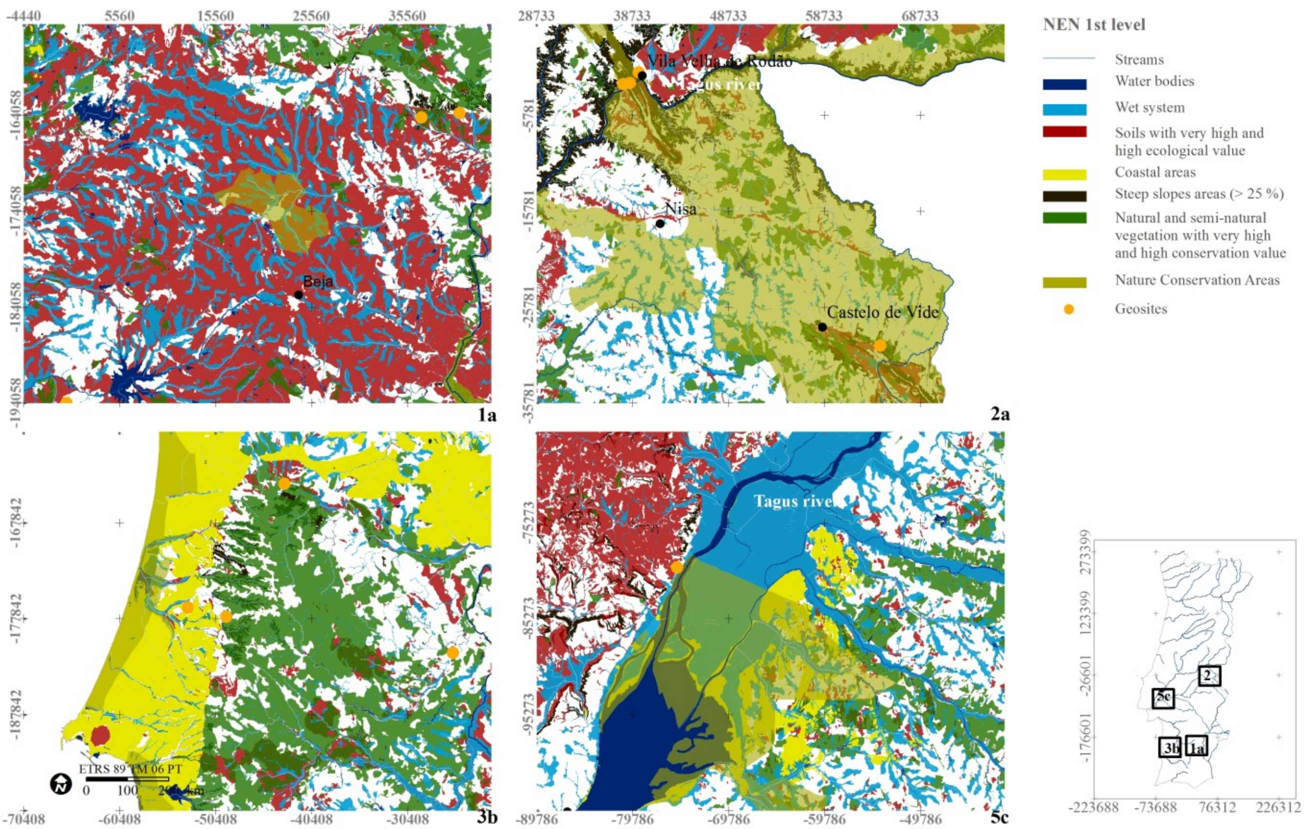

Figure 3.4 NEN1 Details

(6) The coastal area corresponds to 286 928 ha (3.2 % of mainland Portugal). There are few areas that contain five or seven components defined in the NEN1. Despite their obvious ecological value, only 114 771 ha (40 % of the area) is protected within nature conservation areas,

- Natural Park Costa Vicentina is one of the most preserved areas of the Portuguese coast due to it legally high level of restriction for human activities (6a).
- 172 157 ha of the area should be included in protecting areas. In the law, the Coastal Plans (Planos de Ordenamento da Orla Costeira - POOC) only protect a buffer area from 30 m bathymetric up to a 500 m zone from the coastline.
- These areas assumed an important ecological role in protecting Portuguese landscape, by preserving “coastal character”, by maintaining coastal ecosystems functioning and increasing resilience to coastal hazards – important because the urban areas are mostly located in the coastal area

(7) The water component includes streams, marine and coastal waters, transitional (estuaries) and inland waters, and comprises 145 837 ha (1.6 % of mainland Portugal).

- Approximately 57 918 ha (40 % of the area) are under legal protection of nature conservation areas – Tagus (7a) and Sado (7b).

According to the NEN1 components/layers, there are a few areas that contain five or seven components (detailed in Appendix 7B. 2). Most are located in the coastal areas, as shown in Figure 3.5. Despite their ecological value only 1 011 704 ha of a possible 5 951 198 ha (17 % of NEN1) is protected within a legally designated national park, as is seen in Figure 3.4 detail 3b.

Notably, 61 % of NEN1 area results from the individual expression of components in the landscape and 30 % includes areas resulting from the combination of two components presented in the Figure 3.5, usually between soil of a high ecological value and a wet system and between natural conservation areas. Only 9 % of NEN1 is comprised three or more combinations.

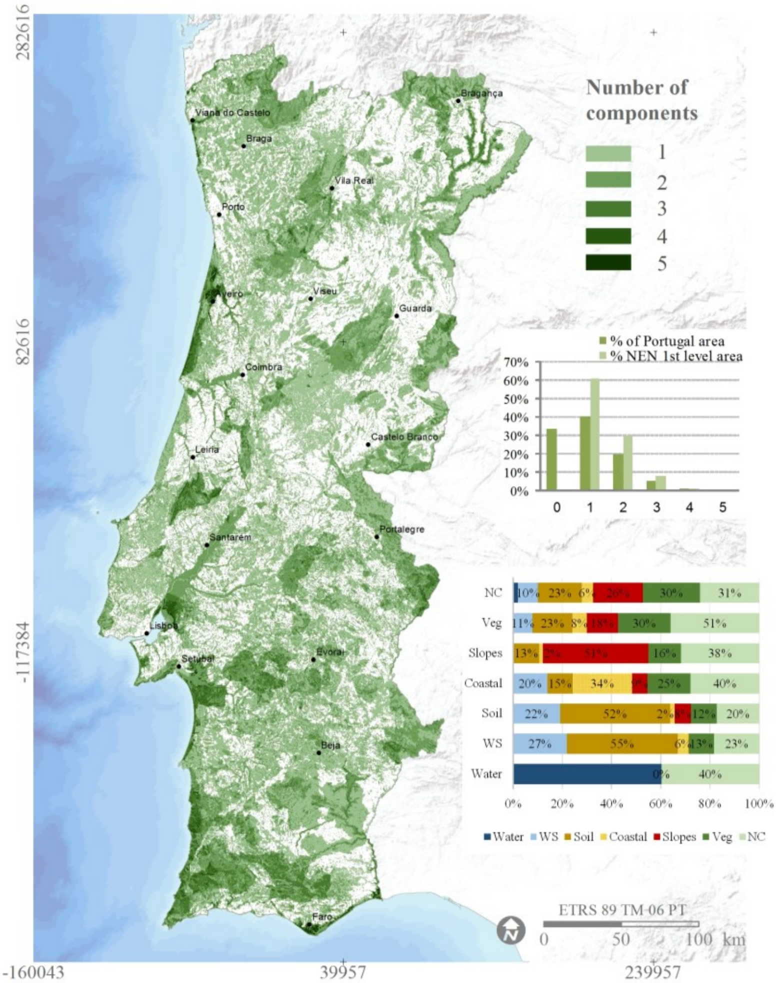

Figure 3.5 Combinations of NEN 1 components

3.4.2 NEN2

According to NEN2 map (Figure 3.6), the most significant layer is maximum infiltration areas (Figure 3.7 detail 8) with 3 768 820 ha (42 % Portugal area), and with 2 298 980 ha (61 % area) already in the NEN1. Also 30 % of the maximum infiltration area is covered by natural and semi-natural vegetation from NEN1 and NEN2. These areas are mainly located in the sedimentary basins of the Tagus and Sado, between Aveiro and Leiria, near to Évora and in the granitic formations of the northern and central Portugal, some areas in Algarve region.

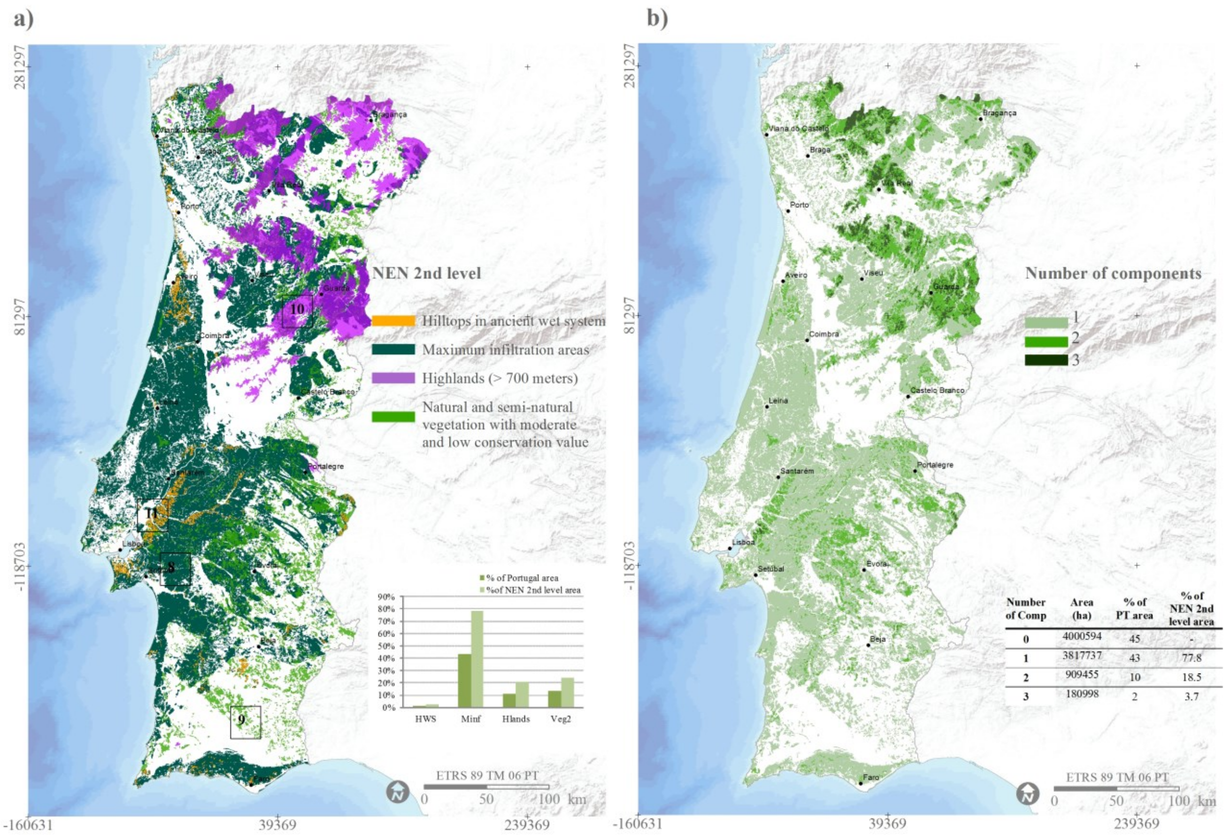

Figure 3.6 Map of NEN 2 a) individual components and b) combinations components

Natural and semi-natural vegetation comprehends 1 203 683 ha of grassland and shrubs (Figure 3.7 detail 9). Generally, there is a higher concentration of areas with conservation value in south of the Tagus River, mostly located in Alentejo. Half coast north of the Tagus River stands out by the notorious lack of vegetation with conservation value, except for the estuarine areas mentioned above and some protected areas, particularly in limestone areas and highlands. 27 % of these areas are located in the highlands. The highlands are closely linked to the bioclimatic levels corresponding to areas with higher than 700 meters elevation, namely Estrela Sierra (Figure 3.7 detail 10) some northern mountains and surfaces plateaus, e.g. Miranda and Beira Interior plateaus, with the exclusion of some low altitude elevations, e.g. the NW sub-coastal mountains, the Extremadura limestones, the Alentejo coastal hills and some Algarve mountains.

Concerning the fluvial terraces (hilltops in the ancient wet system), and given their geological origin, they are to be mainly maximum infiltration areas that correspond to river terraces on the left bank of the Tagus River (Figure 3.7 detail 11).

The results for NEN individual components are presented in Table S.4, which also indicates land management goals and potential land uses.

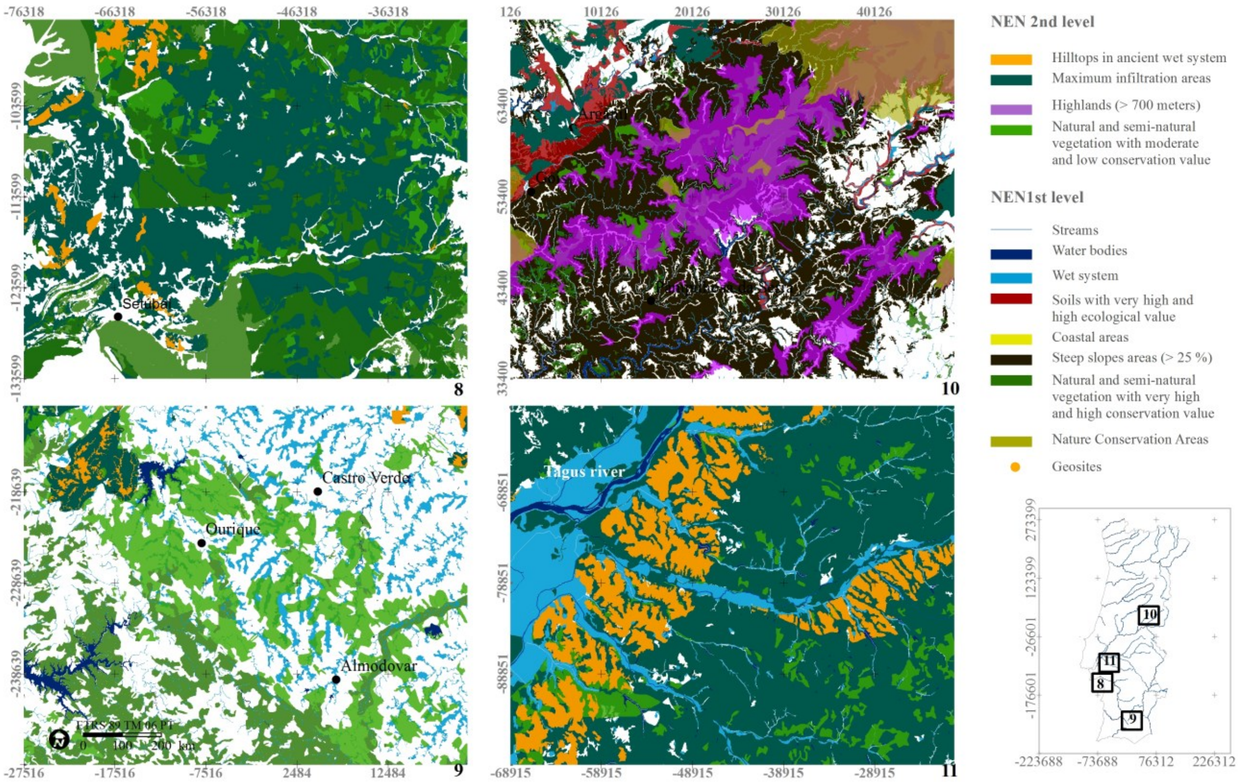

Figure 3.7 NEN2 Details

3.4.3 NEN 1/2

The expected EN for Portugal would be a clearer structure with well-defined core areas and corridors. However, according to this EN mapping method resulted in an interdependent infrastructure where most of the components do not overlap. The results are discussed to clarify if there was an error in the mapping method of NEN or if they are representative of the Portuguese landscape reality. The Portuguese NEN (Figure 3.7) illustrates the mountainous highland North with high productive valley bottoms enclosed by steep slopes, in contrast, with a permeable clay region in the centre, and a southern area constituted mainly by oak trees characteristic of the montado, as a highly productive multifunctional agro-pasture-forestry system. Therefore, the spatial patterns of Portuguese landscape variety result essentially from the relative importance of each individually physical and biological components.

The predominance of the green shades on the GIS maps resulting from this study (Figure 3.8a) shows that a considerable amount of Portuguese land is of environmental importance. The other major difference between the results presented and what was expected due to the stated vertical and horizontal connection of biophysical systems of the EN (Jongman 1995; Magalhães 2001) is the lack of coincidence between certain environmental aspects (Figure 3.8b). For example, one would expect that highly valuable vegetation, from a conservation perspective, is associated with natural conservation areas. However, only 50 % of the area is currently protected and 22 % of such vegetation exists on highly fertile soils. In fact, most highly fertile soil supports agriculture, which although good for food production has little to offer in terms of environmental protection and biodiversity. This challenges the notion that environmentally sensitive and highly valuable ecosystems occur in smaller areas only linked by biodiversity corridors.

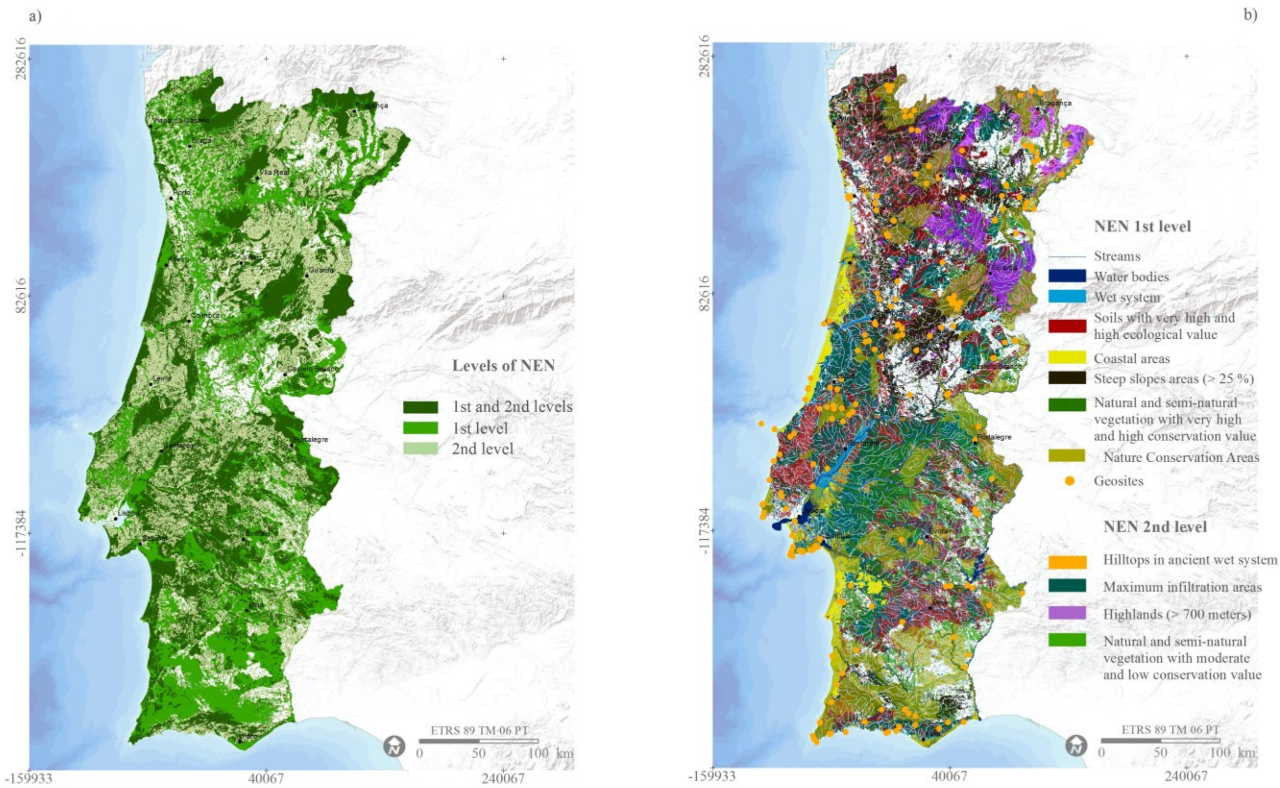

Figure 3.8 a) NEN 1/2 levels; b) NEN 1/2 individual components

The NEN map (Figure 3.8) shows that approximately 12.5 % of the country area has no ecological constraint for building, which means that the ecological value in these areas is not considered significant. In the first evaluation, this value can be considered high, however the currently built-up areas, from the 2007 land use and cover map for Portugal (IGP 2010), represents 4.6 % of the country's area (Figure 3.9). The comparison between the NEN and the built-up areas results that: 2.4 % is built on NEN1 and 0.8 % on NEN2, and only 1.4 % of the non-restriction area is built. If there are nearby existing urban areas they could be assigned for future urban development, including the creation of new urban green areas. The identification and mapping of natural areas and layering them with urban areas support the valuation of the services e.g., willingness to pay for floodplain protection.

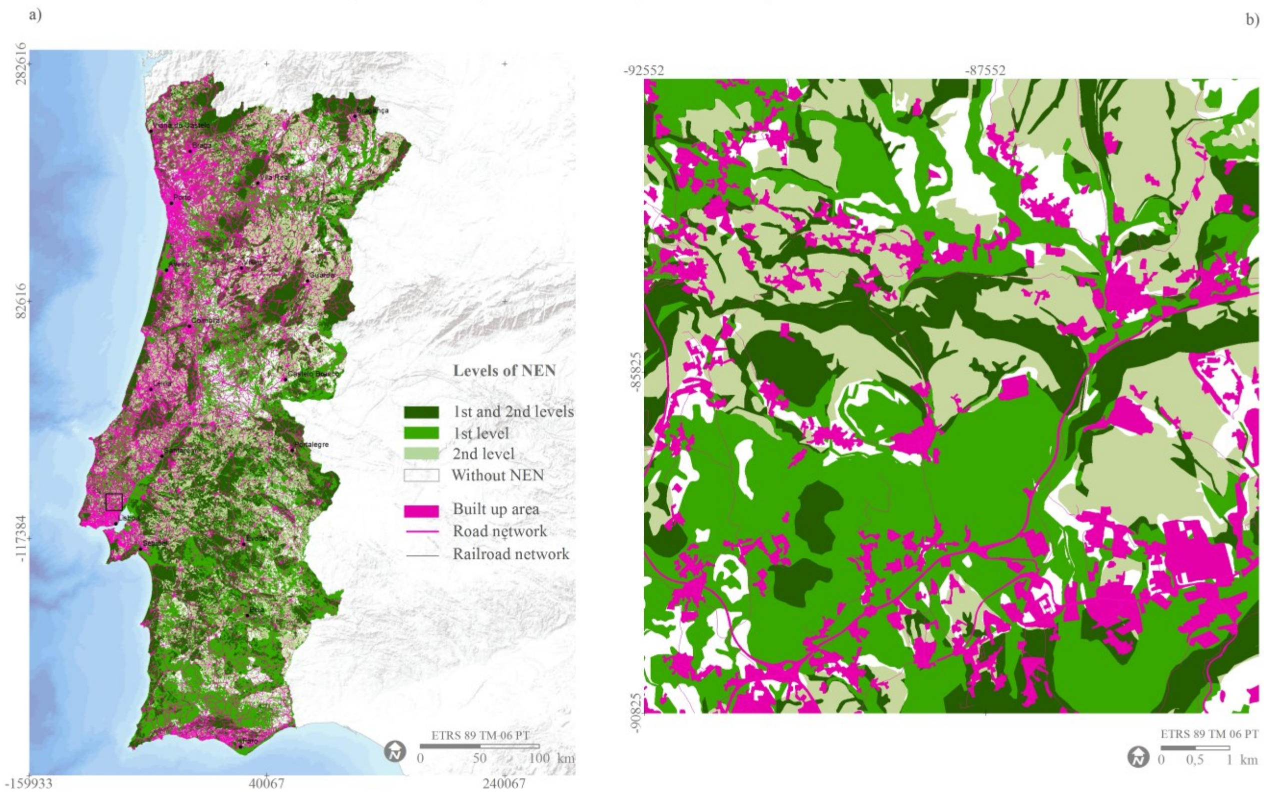

Figure 3.9 a) NEN 1/2 levels with built up area and road infrastructure, b) Detail located in Lisbon metropolitan area

The solution to counteract fragmentation of the landscape, namely in the soils (agricultural), the vegetation (forestry mosaic pattern) and the water system, due to transport infrastructures and urban sprawl, is to implement NEN. The benefits of a Portuguese NEN into a sustainable development, by increasing the ecosystems quality and become less dependent on economic and social activities, are now evident, namely:

(1) From the 67 % of the NEN1 only 8 % corresponds to nature conservation areas meaning that nature conservation areas are not synonymous of the most ecologically valuable areas. These numbers allow the conclusion that the criteria used in conservation areas in previous years, in fact, are insufficient to ensure the ecological balance of landscape, as was determined in the 2011 Biodiversity Strategy.

(2) The NEN can be used as a framework for land-use planning that coupled with at-risk mapping will contribute to limit the consequences of flooding, soil erosion risks and forest fires, decreasing environmental problems and estimated costs of prevention measures.

(3) Improve Portuguese landscape biodiversity in the farmlands, since the change in agricultural land use, characterised by widespread intensification of farming systems on better land and abandonment or afforestation of poorer land, is a major cause of the decline of biodiversity in Europe. It is

estimated that 50 % of all species in Europe depend on agricultural habitats (EEA, 2015). Therefore, the high ecological value soils (28 % of Portugal area) to be included in National Agricultural Reserve (RAN), should encompass farming practices, such as corridors/woods/edges with native species in order to increase the biodiversity value and be qualified as High Nature Value (HNV) farmlands**.**

(4) Due to predictable Portuguese cities depopulation and very high unemployment rates outside the urban municipalities (INE, 2013), EN map should be included in existing spatial plans and programs, in order to promote new challenges for spatial planning, particularly regarding to (i) inclusion of nature-friendly management, (ii) natural heritage and traditions, (iii) spatial accessibility to natural areas, incorporating green areas in urban development models, and (iv) forestall the anthropogenic impact on nature, to contribute to sustainable development strategy.

3.5 | Conclusions

The results shows that it is possible to map EN at a resolution that is sufficiently detailed, with consistent and compatible principles, at the regional and the municipal levels. This is significant because in the Portuguese context, there is no EN map for the national scale and it is understood that the selected NEN components represent the most sensitive areas, and their protection will enhance ecosystem functioning and biodiversity management.

This spatial framework of highly valuable ecosystems represents the first attempt to map Portuguese EN as strategically connected and planned infrastructure rooted in abiotic and biotic systems. This relies on the selection/identification of two levels NEN physical and biological components and the specific mapping methods to assess them and their integration. This NEN addresses the Portuguese planning legal system by considering EN as a unique entity as a comprehensive or adequate network of natural resources and could be included in the National Programme for Land Planning Policy (PNPOT) as a mandatory instrument. This EN delimitation emphasise the quality or potential of physical components in its biological driven base, allowing the articulation with the nature conservation and at-risk areas provided by the other legal instruments.

As similar to the vertical organisation of the central administration, the Portuguese policies are also sectoral and unarticulated. This instrument can be the building block for landscape planning and the basis of the development plans at national, regional and local levels in an integrated manner instead of a compilation of disassociated often contradictory planning tools. Therefore, NEN integrates in a single tool the Portuguese environmental policies more effectively than the RFCN, namely the RAN refers to agricultural use instead of ecological soil value; (ii) the REN mentions the at-risk areas of physical system; (iii) the Public Hydric Domain which is not mapped in Portugal; and (iv) the Nature Conservation Areas, a political and administrative decision to classify habitats and natural areas.

Moreover, since not all ecosystems for Portugal are mapped at national or regional scales, all maps resulting from this initiative are available online and free for download in a platform named EPICWEBGIS, available at http://epic-webgis-portugal.isa.ulisboa.pt/. This could have a huge implication in the future planning system by overcoming missing data on soils, water and vegetation. At the same time, the NEN data layers and EN mapping method can be replicated internationally, just by modifying the ecological thresholds relative to local conditions; and detailed at regional and municipal scales, solving the EN criteria problem, the schematic representation of the networks and the cross-border coherence at regional and municipal levels.

In order to facilitate the implementation of the NEN as a planning tool, the prioritisation should include two major components, (1) as happened in Estonian EN implementation (Külvik et al 2010), priorities based on ecological significance including the importance of ecological resources and the potential for functional connectivity to identify critical landscapes and ecological linkages; and (2) a model assessing development pressure, based on e.g. Baró et al. (2015), to identify areas in NEN for conservation and for restoration. In addition, NEN methodology should be enhanced to articulate the ecological and cultural functions, to be considered as a legal framework for the future Portuguese GI.

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3.7 | Supplementary material

Table S3.1 Relation between Ecological Network and the other Portuguese landscape planning tools at the national, regional and municipal level.

	NATIONAL		REGIONAL	MUNICIPAL
	PNPOT	**RFCN**	**PROT**	**PMOT**
EN	-	-	ERPVA	EEM
DPH	Natural systems and agroforestry	Continuity Areas	Strategic Guidelines and risk areas	Restriction Areas
RAN				
REN				
NSCA		Core Areas	Conservation Areas	Natural Areas
Conservation Areas Natura 2000, IBAs, Ramsar list, Biosphere and Biogenetic Reserves				

Note: EN – Ecological Network, DPH - Public Hydric Domain, RAN - National Agricultural Reserve, REN - National Ecological Reserve, NSCA - National System of Classified Areas, PNPOT - National Program for Land Planning Policy, RFCN - Fundamental Network of Nature Conservation, PROT - Regional Land Management Plans, PMOT - Municipal Land Management Plans, ERPVA - Regional Structure Plan for Environmental Protection and Enhancement, EEM – Municipal Ecological Network

Table S3.2 Data collected and assessed.

System	Subsystem	Existing Data	Assessment	Explanation	References
Physical	**Water**	Streams and watersheds (INAG 2010), water bodies and wetlands from COS 2007 (IGP 2010). Satellite images (ESRI Base Maps® 2011) Military Maps of Portugal - M586 Series, scale 1/250 000 (IGeoE).	Hydrological network	The streams were ranked into four levels according to their watershed areas and their streams length and the ridgelines were generated from the watershed boundaries.	(WFD. 2102; Silva et al., 2013a).
	Land morphology	DTM (IGP 2010) Water subsystem (Hydrological network)	Landforms	The landscape form that arises from its main physical structures is characterised by two different ecological systems in the landscape: the wet system and the dry system and three general landforms: 1) valley bottoms, including streams, permanent and temporary, water bodies, inland and coastal wetlands; 2) hillslopes and 3) hilltops, including ridges and large hilltops.	(Magalhães, 2001, Cunha et al., 2013, Cunha et al., 2017)
	Soil	Soils map Scales 1/100 000 and 1/50 000 (UTAD/DRAEDM/ DGADR/ SROA)	Soil Ecological value	This work was developed using an inventory of soil maps with three different soils classifications: FAO (FAO 1988) in North, WRB (FAO/WRB 2006) in centre, both with 1/100 000 scale, and the Portuguese soil classification (Cardoso 1974) in the coastal central area and the south of Portugal at 1/50000 scale. Classification based on intrinsic characteristics – thickness, fertility and conservation interest related to a particular ecosystem, e.g., associated with traditional agricultural and forestry systems.	(Cortez, 2007, Leitão et al., 2013a)
	Geology/ Geomorphology	Geology maps at 1/10^6, 1/500000, 1/200000, 1/50000 (LNEG/IGM, several dates), Hydrogeology maps at 1/10^6, 1/200000, 1/100000 (LNEG/SGP, several dates) Aquifers maps unscaled (INAG/SNIRH, 2000), Corine Land Cover CLC 2006 at 1/100000 (IGP/EEA 2009) COS 1990 (IGP 1990)	Subsoil and soil permeability	A qualitative evaluation of groundwater infiltration capacity considering the geological substrate, soil and slope and the influences of soil cover. Also includes occurrences of natural geodiversity with exceptional scientific value, where minerals, rocks, fossils or geoforms have characteristics that represent the geological history of our planet.	(Pena and Abreu, 2013, Pena et al., 2016) (Brilha et al., 2013)
	Climate	DTM, soil and land cover (USGS)	A climate data reconstruction (2000 – 2009)	The calculation of many variables, for every hour, in a 9x9 km surface grid, 35 levels in height and four levels of soil depth, up to two meters. This includes average maximum and minimum temperatures, average daily and extreme minimum temperatures, average wind speed, wind speed standard deviation relative to average and extreme maximum wind speed.	(Domingos et al., 2013)
Biological	**Vegetation**	Natural and semi-natural vegetation predictive map (or vegetation series map)	Natural and semi-natural vegetation conservation value	A phytosociological basis methodology for obtaining predictive vegetation map relies on the determination of landscape vegetation composition from known and mapped environmental variables. A potential vegetation map which is then intersected with current land use maps, in order to estimate the total areas assigned to the different types of natural vegetation. The conservation value is evaluated based on five parameters: naturalness, replicability – concerning the regenerative capacity of the community, endangerment, floristic richness and rarity.	(Capelo et al., 2007, Mesquita, 2013)
	Nature Conservation Areas	Natura2000; Important Bird Areas; Wetlands – Ramsar Convention; Biosphere and Biosphere Reserve; National network of protected areas		Compilation of all data to establish legally protected areas for nature	(Leitão et al., 2013b)

Table S3.3 Relation between NEN systems, subsystems, components and environmental service benefits

Subsystem	GIS code	NEN components	Definition	Environmental Services Benefits
Water	1	Streams	Ranked into four levels according to their watershed areas and their streams length. The 1st level corresponds to a river catchment area greater than or equal to 500 km² and a total section river length longer or equal to 15 km (WFD, 2012), that drains directly into the sea. The 2nd level of the stream is identical to the first with the exception that it does not drain directly into the sea and its streams are tributaries of 1st levels. The 3rd level corresponds to streams with high regional significance, a watershed drainage area of less than 10 km², and a stream length exceeding 2 km. Finally, the 4th level integrates streams that have a smaller territorial expression but relatively local importance. This level corresponds to those which were not included in previous ones (Silva et al., 2013a).	Hydrological cycle continuity, hydrologic and hydraulic functionality Land drainage, flood control, streams naturalisation Natural habitat conservation Riverbank protection with riparian vegetation leading to erosion control Water quality improvement
		Marine and coastal waters	Saltwater areas extending to the outer boundary of transitional waters.	Water quality improvement and maintenance Effluent discharge requirements Prevention and reduction of coastal risks Natural habitats conservation
		Transitional waters (estuaries)	Bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters but which are substantially influenced by freshwater flows.	Riverbanks protection with riparian vegetation Fluvial-marine balance and dynamic maintenance Tide and wave damping; water purification Natural habitats conservation, biological production
		Inland waters	All standing or flowing water on the surface of the land (permanent, seasonal, or intermittent occurrence in flooded conditions) and all groundwater on the landward side of the baseline from which the breadth of territorial waters is measured.	Water cycle regulation, Flood control Filtering and improvement of water quality Riverbank protection with riparian vegetation Natural habitat conservation
Land morphology	10	Wet System Valley bottoms	The WS includes permanent and temporary streams, water bodies, wetlands and valley bottoms. Valley bottom is a broad concept which comprehends not only floodplains but also flat and concave areas, contiguous to streams, in which slope is less than 5 %. With this definition, in downstream areas of the watersheds, valley bottoms are generally wider, more humid and directly influenced by groundwater level, which enhances flooding risk, and consequently are coincident with the floodplain; The upstream areas are characterised by a higher soil moisture coming from runoff water (Cunha et al., 2017).	Water cycle regulation - storage and distribution of freshwater and accumulation of nutrients Assurance of water infiltration and retention in natural conditions Geomorphological stability Maintenance of soil fertility and productive capacity Flood prevention and mitigation
		Wetlands	Inland wetlands comprising reed beds, cane field, rush field and bogs (INAG 2010; IGP 2010); and coastal wetlands, including marshes, salt marshes and coastal aquaculture (IGP, 2010).	
	1000	Coastal areas	This includes the continental shelf (200 meters isobaths including 30 meters bathymetry), coastal wetlands, marine, coastal and transitional waters marine, islands or islets, beaches, cliffs, geological formations (Quaternary), deposits of marine terraces (Silva et al., 2013b).	Conservation and balance of dynamic coastal processes Prevention and reduction of coastal risks Coastal communities protection from human interference Landscape heritage and aesthetics
	10000	Steep slopes	Hillslope areas with a slope greater than 25 %. Generally, they are associated with high erosion levels and loss of soil because of superficial or deep mass movements.	Soil conservation and regeneration Maintenance of morphogenetic and pedogenic processes balance Water cycle regulation Infiltration and retention of rainwater increment

Table S3.3 Relation between NEN systems, subsystems, components and environmental service benefits (cont.)

Subsystem	GIS code	NEN components	Definition	Environmental Services Benefits
Land morphology (cont)	2	Hilltops in ancient wet system (Pleistocene fluvial terraces)	A subclass of hilltops that constitute Pleistocene fluvial terraces (or hilltops in ancient wet system). Such landforms correspond to the flattened areas that, border the wet system but are not situated in valley bottoms, since they are at a higher altitude even though the flood risk is real. The soils developed from them can no longer receive the addition of alluvial sediments and have a high organic matter content and usually have the groundwater at a deeper level relative to Fluvisols or Alluviosols, e.g., Ancient Alluviosols (Cunha et al., 2013).	Geomorphological stability Water infiltration increment Landscape heritage
	200	Highlands	Areas with an altitude of 700 meters, corresponding to the following bioclimatic levels (or thermotypes): supra-temperate, supra-Mediterranean and oro-temperate (Mesquita 2005). This criterion was based on the mountain concept used in the Millennium Ecosystem Assessment project for Portugal by Aguiar et al., (2009) as homogenous area from a bioclimatic, agrarian, social and, social and ecosystems services point of view.	Geomorphological stability. Increasing pedogenic processes
Soil	100	Soils of very high and high ecological value	This includes soils with considerable soil depth and the highest rates of fertility, e.g. Fluvisols, Anthrosols, Humic Cambisols (FAO and WRB classifications) and Alluviosols (Portuguese classification) as well as soils associated with traditional agroforestry ecosystems, associated with specific ecosystems, e.g., marshes (Leitão et al., 2013a).	Soil conservation and regeneration Maintenance of morphogenetic and pedogenic processes balance Soil fertility improvement
Geology/ Lithology Geomorphology	-	Geosites	Presented as part of the national inventory of geological heritage, analysed to identify the geological occurrences of exceptional national and international scientific relevance in Portugal. In addition to having scientific value, these occurrences may also have an educational and touristic value (Brilha et al 2013).	Protection and enhancement – classification Centre for environmental interpretation Landscape heritage and aesthetics
	20	Maximum infiltration areas	Areas that have high permeability resulting from the evaluation of geology, soil, slope and land cover. These areas are important locations of potential areas of groundwater recharge, contributing to decrease the unorganised runoff and erosive processes, to increase freshwater reserves supplies and water availability and to maintain the balance of the landscape geomorphological dynamics (Pena and Abreu, 2013; Pena et al., 2016).	Ensure infiltration and protection of groundwater quality Water cycle regulation Reduced risk of saline intrusion (coastal aquifers) Sustainability of ecosystems dependent on groundwater
Natural and semi-natural vegetation	100000	Very high and high conservation value	This includes vegetation in coastal and estuarine areas, mountain areas, forests, woods and meadows with high biodiversity or rare species	Maintenance and management of natural and semi-natural vegetation Landscape heritage and aesthetics
	2000	Moderate, low and very low conservation value	This includes areas where the vegetation is natural or semi-natural but the conservation value based on floristic richness and rarity is not high enough yet to be considered endangered. The regenerative capacity of such areas is important to the wildlife community e.g. annual grasslands, meadows with low biodiversity (Mesquita, 2013).	Maintenance of natural vegetation and restoration of degraded ecosystems Biodiversity conservation
Nature Conservation Areas	1000000	Nature 2000 Important Bird Areas Wetlands - Ramsar Convention Biosphere and Biosphere Reserve National network of protected areas	This includes Nature 2000 areas, national parks, nature parks, nature reserves, protected landscapes, natural monuments and protected areas with private status.	Biodiversity and ecosystem conservation Landscape heritage and aesthetics

Table S3.4 NEN individual component results and observations.

	NEN components	% area PT	% area NEN1	% area component (the most relevant combinations)	Description	Observations	Land management goals and potential uses
(1)	Soils of very high and high ecological value	**28 %**	**42 %**	52 % of the area exists by itself	These areas are in the dry system (hilltops and hillslopes) and constitute highest productive soils of the country	**(1a)** Particularly a productive area with clay soils in Alentejo in south Portugal and near to Lisbon	Irrigated or dryland farming, compartmented, woods with native species Only rural settlements (agricultural supports)
				22 % is located in the wet system	These soils in the wet system are usually recent Alluvisols/ Fluvisols developed on alluvial deposits	**(1b)**These soils have an increased fertility value high productive valley bottoms enclosed by steep slopes of the mountainous highland North	
(2)	Nature conservation areas	**25 %**	**37 %**	50 % is coincident with one other NEN1 component	Nature conservation total area protect only one other physical or biological component	Nature conservation areas are not synonymous of the most ecologically valuable areas They do not protect all the systems – especially the physical system of the landscape and only half of the area of natural vegetation	Agroforestry systems that ensure biodiversity conservation and ecosystems balance Native plant and animal species protection
				31 % of nature conservation areas exist by themselves	Serving only their biodiversity conservation purposes.		
(3)	Vegetation with very high/ high conservation value	**15 %**	**22 %**	50% is protected by nature conservation areas.	half of these areas are outside of nature conservation areas, namely Natura 2000	**(3a)**These areas have high floristic richness and rarity, and if not protected the regenerative capacity of the community is in danger	Agroforestry systems Grazing in the under covered Nature conservation Research, environmental education, scientific and nature tourism
				30 % do not combine with other components of the NEN.	particularly adapted to extreme conditions of climate, soil and water availability	**(3b)** mostly oak forests (*Quercus suber and Quercus rotundifolia*) in southern Portugal. These areas are protected by specific national legislation	
(4)	Steep slopes	**17 %**	**26 %**	50% do not combine with other NEN1 components	Situated mostly on hills or hillsides of narrow valleys, especially in hard lithology	**(4a)** Centre of Portugal in Estrela Sierra Algarve Sierra and in the most situations is not correctly covered with adequate vegetation	Bushes, woods and forest protection Wood production Agriculture or permanent meadow in terraces Building construction only in terraced land
				15 % is protected with natural or semi-natural vegetation	Only in these areas the soil is correctly covered with adequate vegetation	The soil erosion risk is enhanced by incorrect land use practices	
(5)	Wet system	**11 %**	**17 %**	50% is combine with another component	High productive soils that cannot be sealed and building restricted	**(5a)** Soils of high ecological value (Fluvisols and Coluviosols).	Riparian gallery, natural meadow, riverine forest, agriculture irrigation systems Building restricted, only indispensable collective facilities with flood protection
				23 % is classified as nature conservation area	Wetlands - Ramsar Convention	**(5b)** Minho and Lima Rivers, Ria de Aveiro, Tagus Lezíria (alluvial agricultural field) Floodplain, Faro and Vila Real de Santo António Campina (farming land)	
				13 % is covered by natural or semi-natural vegetation	Riparian gallery and riverine forest	These areas have a high biodiversity value and must be preserved	
(6)	Coastal areas	**3 %**	**5 %**	50 % corresponds to at least two or three components simultaneously	These areas assumed an important ecological role in the NEN in preserving “coastal character” by maintaining coastal ecosystems functioning and increasing resilience to coastal hazards	Justifies its high level of restriction for human activities.	Building restricted to beach facilities and ports

Table S3.4 NEN individual component results and observations (cont.).

	NEN components	% area PT	% area NEN1	% area component (the most relevant combinations)	Description	Observations	Land management goals and potential uses
(7)	Water	**1.6 %**	**2.5 %**	40 % corresponds to nature conservation areas	Tagus and Sado estuaries	The water system protected by another legislative framework (REN and DPH)	Small infrastructure to support agricultural activity and recreation Fisheries support Marine production and aquaculture
(8)	Maximum infiltration areas	**42 %**	**78 % NEN2**	(**8**) 61 % of the area is in NEN1	17 % with natural vegetation 1st level 15 % with natural vegetation 2nd level	Mainly located in the sedimentary basins of the Tagus and Sado, between Aveiro and Leiria, near to Évora and in some areas in Algarve region.	Mixed woods of conifer and broadleaf trees, permanent meadows, agriculture with integrated protection Building construction only permitted after sustainability concerns met, as defined by Portuguese legislation
(9)	Natural and semi-natural vegetation (2nd level)	**13 %**	**21 % NEN2**	63 % is coincident with other NEN 1 components	27 % of the area is in highlands		Restoration of strategic areas with higher conservation value
(10)	Highlands	**12 %**	**21 % NEN2**	60 % of area coincident with other NEN1 components	40% in NEN2 and 13% of the area exist by itself	Mountain agro-pastoral production systems - semi-natural meadow pastures (lameiros) associated with farming, grazing, woods, protection and production of the forest	Biological diversity conservation and encouragement of traditional management practices Small scattered settlements
(11)	Fluvial Terraces (hilltops in the ancient wet system)	**1.4 %**	**2.6 % NEN2**	83 % of the area is maximum infiltration areas	Correspond to river terraces on the left bank of the Tagus River	Given their geological origin these Pleistocene river terraces	Agriculture, permanent meadows, riverine forest Small scattered settlements

4 | THE LAND MORPHOLOGY CONCEPT AND MAPPING METHOD AND ITS APPLICATION TO MAINLAND PORTUGAL

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4 | THE LAND MORPHOLOGY CONCEPT AND MAPPING METHOD AND ITS APPLICATION TO MAINLAND PORTUGAL

Abstract

Land morphology influences and shapes the distribution of biodiversity, agricultural production and economic activity. It can be systematised into landforms. This paper shows that landforms can be quantitatively categorised and mapped using the land morphology concept (LMC) and mapping (LMM) method. The LMC classifies landforms according to their hydrological position in the watershed. The LMM method used three criteria: flat areas (slopes less than 5 %), surface curvature and hydrological features. This methodology was employed to create a 25 m spatial resolution GIS map of mainland Portugal's land morphology and landforms elements. This map was compared with the distribution of soils from wet system in order to interpret local dynamics/relationships between soils distribution and landforms, and was also compared with two widely known automatic landform classifications. Therefore, it may contribute to enhance ecological land unit's maps.

By specifically distinguishing valley bottoms and hilltops from flat areas, an atypical practice in landform classification, this method is a helpful evaluation tool for modelling natural systems, namely floodplains, across regions and countries (simply by modifying the slope gradient) and an input layer to map ecosystem and ecosystem services accurately.

Research highlights

- Land morphology quantitatively categorised and mapped landforms.
- Wet and dry systems are composed by valley bottoms, hillslopes and hilltops.
- Mapping of concave-convex surfaces was undertaken relative to the hydrological network.
- Valley bottoms and hilltops can be distinguished from flat areas.
- Soils located in the Portuguese wet system may not have been correctly classified.

Keywords •Automatic landform classification •Landform elements •Mapping method •GIS •Wet and dry systems • Soils from the wet system

4.1 | Introduction

One of the most complex issues that modern society is facing is fast landscape transformation and fragmentation (ECNC, 2003; Jaeger et al., 2011; Tillmann, 2005). The result is a decrease in biodiversity and the decline of ecosystems quality and services (Mücher et al., 2010). Landscape, and by extension land morphology, should be regarded as a multifunctional resource to which a wide range of ecosystem services are associated (EEA, 2014).

Land morphology influences and shapes the distribution of biodiversity, agricultural production and economic activity. It can be systematized into landforms, as a functionally interrelated part of the land surface (Pike et al., 2009). For any given scale, landforms can be quantitatively categorised and mapped using the land morphology concept (LMC) and land morphology mapping (LMM) method. The LMC is used to define the landscape form that arises from its dominant physical structures, linking together the topological and hydrological features. The LMC provides a means to classify the wet and dry systems in the hillslope profile, and supports an understanding of ecological functioning by classifying landforms according to their hydrological position. Therefore, the LMM method constitutes a dynamic and syncretic tool used to evaluate the trade-offs between ecological functioning and cultural appropriation (Magalhães, 2001).

This work’s principal objective is to establish and validate criteria with which to standardize the LMM method, and create a geographical information system (GIS) land morphology map, with a detailed 25 m spatial resolution, for mainland Portugal. The resulting map was compared and validated against previously constructed GIS maps for Portuguese soils and two widely known automatic landform classifications (Jenness, 2006; Sayre et al., 2104).

The LMM map and data obtained may be used for land use delimitation and optimisation, in order to, for example, provisionally delimit floodplains and potential flood risk areas (Cunha et al., 2017), and whilst also identifying in planning and decision-making process multiple and competitive land uses. This is of significant value for the Portuguese Government and the European Union.

4.2 | State of art

Land morphology controls or influences surface water flow, transport of sediments, soil genesis and soil productivity (Huston, 2005), local and regional climate, and the distribution of vegetation (Blaszczynski, 1997; Minár and Evans, 2008). Therefore, it affects biodiversity, agricultural production and economic activity (Huston, 2005). In the same way, human action influences the landscape and is an agent of landform transformation, which can be quantitatively demonstrated in a GIS map.

Landform mapping is an essential tool in different applications (i) ecological land units (Bailey, 2009; Gerçek, 2017; Mücher et al., 2010; Sayre et al., 2014;) (ii) terrestrial ecosystems, including their restoration (Cress et al., 2009; Palik et al., 2000; Sayre et al., 2009) and their services (Burkhard et al., 2013; Dickson et al., 2014 ; Maes et al., 2014; Petter et al., 2012) (iii) watershed modelling (Morgan and Lesh, 2005), (iv) predictive soil identification (Barringer et al., 2008; MacMillan et al., 2000; Mulder et al., 2011; Pennock and Corre, 2001) (v) soil erosion (Naipal et al., 201; Zhang, 2002;) and (vii) modelling fluvial processes and floods (Cunha et al., 2017; Osterkamp and Hupp, 2010).

Due to this applicability in various fields, the classification of the landscape into landforms has been widely reviewed. Basically, landform classification is the attempt to organize the complexity of the Earth's surface into a limited number of easily discernible functional units (Burrough et al., 2000). This requires methods to quantify its form and subdivide it into more manageable components. Those methods classify landforms into (i) homogeneous regions of the earth's surface in terms of land surface parameters such as slope gradient, elevation and curvature (*e.g.* Dalrymple et al., 1968; Drăguţ and Blashke, 2006; Gerçek, 2010; Hammond, 1964; Iwahashi and Pike, 2007; Minár and Evans, 2008; Wilson and Gallant, 2000), or (ii) specific geomorphological features or landform elements, *e.g.* hillslope forms (Burrough et al., 2000; Dikau, 1991; Irvin et al., 1997; Jasiewicz and Stepinski, 2013; MacMillan et al., 2000; Wood, 1996).

These classifications are also based on the physical, topographic and hydrological characteristics of the surface. Topographic method was originally established by Hammond (1964a, b). It was manually executed and focused on three topographic variables: slope, local relief, and profile type. This method was automatized in GIS by Dikau et al. (1991) and improved by several other authors, mentioned in Table S4.1. A widely applied topological classification is the Missouri Resource Assessment Partnership (MoRAP) model elaborated by True (2002). It was recently applied to global ecological land units (Sayer et al., 2014). This model is simple in the sense that it only considers (i) average slope, classified into two classes, gently sloping (< 8 %) or sloping (> 8 %), and (ii) relative relief, the difference between the maximum and minimum elevation of the neighbourhood.

There are also hydrologically based methods for modelling landforms. They focus on hydrological and drainage networks, as shown in Table S1, and the shape of hillslopes and valleys are linked to transport mechanisms and erosion processes (Dietrich et al., 2003; Sweeney et al., 2015). An example of this type of classification is the Topographic Position Landforms analysis (TPI method) developed by Weiss (2001) and computerised by Jenness (2006) into an ArcGIS ESRI® script. As scale dependent methods, also with the TPI in larger neighbourhoods, topographic details tend to disappear (Weiss, 2001). The TPI method relies on the difference between a cell elevation value and the average elevation of the neighbourhood around that cell, within a predetermined radius (Weiss, 2001; Wilson and Gallant, 2000). This method categorize the landscape into two levels. The first one is slope position, and identifies (i) hilltops – which are higher than their surroundings and (ii) valley bottoms – which are lower than the surrounding neighbourhood. Values close to zero, represent either a flat or a mid-slope area distinguished by a threshold of ± 5°. The second level is landform category, determined by the combination of values from different scales, *e.g.* a low small-neighbourhood combined with a high large-neighbourhood is classified as upland drainage or depression (Jenness, 2006).

Both physical classifications tend to focus on landscape discontinuities in the hillslope profile (Huggett, 2011). Such discontinuities are usually associated with a change in the dominant surface process and linked to environmental land properties, such as geological/lithological, pedological, vegetation characteristics and hydrological conditions (MacMillan et al., 2004; Romstad and Etzelmüller, 2012; Speight, 1974). Therefore, they often indicate the boundary between adjacent geomorphological units on a map (Giles, 1998; Minár and Evans, 2008; Pike et al., 2009).

The LMM method is a physical method that classifies landform elements according to both topographic and hydrological characteristics. The LMC, established by Magalhães (1993) and expanded by Magalhães (2001) can be used to define the landscape form arising from its dominant physical structures, linking together the topological and hydrological features. It typifies two systems in the hillslope profile, as shown in Figure 4.1.

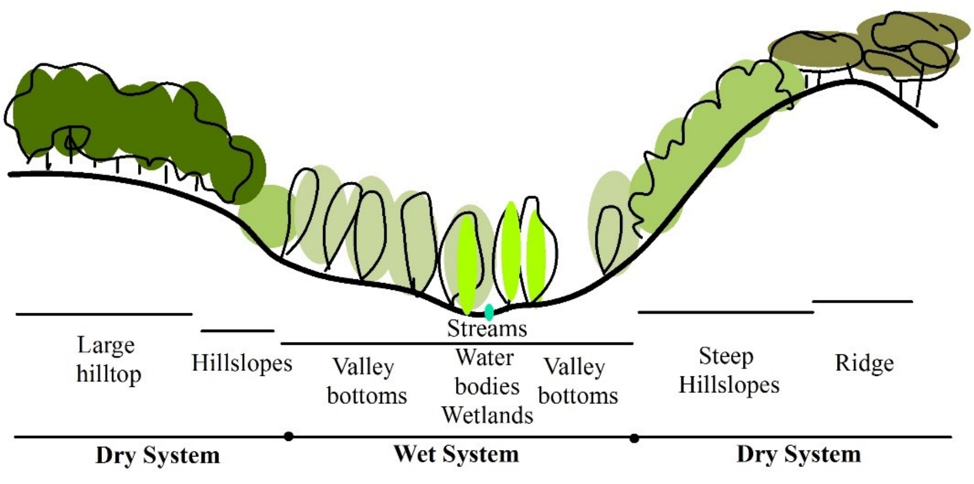

Figure 4.1 Land morphology concept schematic profile.

The wet system is characterised by surface water accumulation, soil fertility due to nutrients accumulation/retention, riparian and wetland vegetation, and cool air accumulation at night (Geiger, 1965; Magalhães, 2001). It is highly sensitive to change and has significant ecological value, because it plays a critical role in water balance specifically in flood risk management, providing a variety of provisioning, regulatory and supportive functions (Cunha et al., 2017) and acts as an ecological corridor (Wickham *et al.*, 2010). It consists of:

(i) Linear features, such as permanent and temporary streams, and water bodies including marine and coastal waters, transitional (estuaries) and inland waters (COS, 2007; IGP, 2010);

(ii) Inland wetlands comprising reed beds, cane field, rush field and bogs, and coastal wetlands including marshes, salt marshes and coastal aquaculture (INAG, 2010; IGP, 2010);

(iii) Valley bottoms including floodplains, also referred to as "areas contiguous to streams": These are defined as flat or concave areas adjacent to streams with a slope < 5 %. This is because above this value water infiltration retention begins to decrease and runoff increases (Magalhães, 2001; Wysocki et al., 2011). Furthermore, the term "valley bottom" encompasses both the upstream and downstream components of the watershed. The upstream areas are characterised by a higher soil moisture coming from runoff water, and downstream areas coincide with the floodplain (Cunha et al., 2017). They are referred to by FAO (2001) as "wetlands" or "lowlands" and are commonly situated near sea level and consist mainly of alluvial deposits.

The dry system encompasses convex slope areas, commonly found on the upper parts of the hillslope profiles, where soil erosion and subsurface and surface water movement are dominant processes (Huggett, 2011). It includes:

(i) Hilltops: They are defined as convex areas with slope < 5 %. These areas vary in width due to erosion processes. The narrower forms correspond to the ridgeline and the wider to large hilltops, which are commonly referred to as plateaus.

(ii) Hillslope or hillside: These landforms are vulnerable to soil erosion, especially those where the slope is > 25 %. Another characteristic of this landform is the "thermal belt" due to the drainage winds that carry colder air downslope to the valley bottom. Consequently, they turn out to be the most ecologically suitable areas for urban development (Magalhães, 2001; Magalhães et al., 2011). The term "hillslope" encompasses both the hillslope and hillside.

The LMC was first established by Magalhães (1993) and applied to the land morphology mapping of Lisbon manually executed. It was featured in the municipal Ecological Network established in the Plano Verde de Lisboa (Lisbon Green Plan) (CML, 2012; Telles et al., 1997). The LMC was applied elsewhere in Portugal and drawn according to local features (Magalhães et al., 2002), and at regional scale for Lisbon Metropolitan Area (Franco et al., 2013; Magalhães et al., 2003).

4.3 | Study area

Mainland Portugal covers an area of 92,212 km² and is home to approximately 10,6 million inhabitants (INE, 2012). Two metropolitan areas, Lisbon and Porto, hold 43 % of the total population. Portugal's longest river, the Tagus, splits the mainland into two clearly identifiable landscapes.

According to the hypsometric map (Figure 4.2a), elevations of less than 400 m occur in more than 70 % of the territory (almost 65,500 km^2). The area north of the Tagus River comprises 95 % of those elevations above 400 m. The highest points are in Estrela and Gardunha Sierras, as marked by the redder colours in Figure 4.2a. Relief south of the Tagus River shows pedeplain characteristics with gently wavy hills and extensively depressed river basins. Approximately 62 % of this landform forms part of what is frequently defined and mapped as lowlands (< 200 m elevation). Steep slopes (Figure 4.2b) prevail in the north and in Algarve Sierras. There is however no dominant slope class, as shown in Figure 4.2b (2).

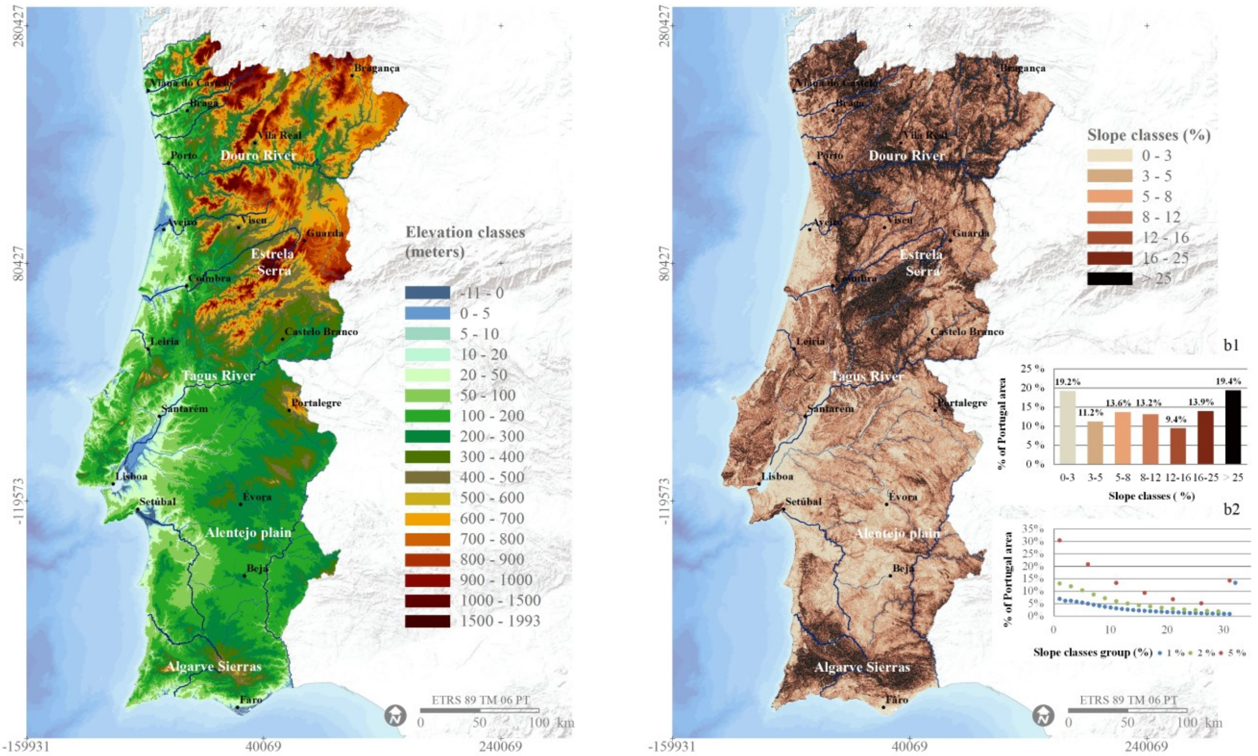

Figure 4.2 Mainland Portugal's physical characterization a) Hypsometric map with major rivers (INAG, 2010) and b) Slope map and frequency of slope in mainland Portugal defined by group classes of 1 %, 2 % and 5 %. Source: by the Authors based on DTM from INAG (2010).

According to Pereira et al. (2014), mainland Portugal is divided into three main geomorphological units of the first level: (1) The Iberian Massif, which constitutes 70 % of the mainland Portugal and mainly consists of granites and schists;

(2) the Iberian Mesozoic Basin, which is slightly deformed and represented in Portugal by two sedimentary basins, the Lusitanian and the Algarve, comprising the limestone massifs of Estremadura, Arrábida and Algarve among other sedimentary rocks;

(3) the Cenozoic basins represented by (i) the Tagus and Alvalade basins including the Lower Tagus plain with the alluvial and low sedimentary Pleistocene terraces of the Tagus River, (ii) the Douro and Guadiana basins (with very low representativeness in Portugal), corresponding to plateau areas in Cenozoic sediments, and (iii) coastal plains (marine and alluvial in origin).

Relatively to soil types (FAO, 2014), according to a simplified soil map of Portugal (based on Cardoso et al., 1973), the most extensive soils in mainland Portugal are: Cambisols followed by Leptosols and Luvisols. Cambisols were developed on medium and fine-textured materials derived from granite in the north and limestone massifs of Estremadura. Most of these soils have intensive agricultural land use. Leptosols are soils with a very shallow profile depth, and they often contain large amounts of gravel. They typically remain under natural vegetation, being especially susceptible to soil erosion, desiccation, or waterlogging, depending on climate and topography. These soils dominate in Trás-os-Montes, Beira Interior and Alentejo, usually developed on schist. Luvisols, which are characterized by a subsurface horizon (argic B horizon) with higher content of clay that has migrated from the surface horizon, dominate the flat lands of the Alentejo, between Beja and Portalegre. Fluvisols are found typically on lowlands that are flooded periodically by surface waters or rising groundwater, as in alluvial plains and in coastal lowland. In Portugal they are located, mostly, in lowland areas of large rivers, such as the Tagus and the Mondego. These soils, albeit with some minor differences, corresponds to the following soil types from the Portuguese classification (Sousa et al., 2004): Recent Alluvisols, Ancient Alluvisols, Colluvisols, and Organic Hydromorphic Soils. Ancient Alluvisols correspond mostly to soils developed on Pleistocene river terraces, which are typically situated at a higher altitude than the recent alluvial plain, and characterised by no recent addition of alluvial sediments and where the groundwater level is located more deeply.

4.4 | Method

A method for selecting an appropriate slope for use on the national level is required in order to depict and describe Portugal's landscape at a resolution that is sufficiently detailed to capture the Portuguese heterogeneous landscape and distinguish the wet and dry system, in a specific situation of gently wavy relief, where the hillslope is absent. In this section, a method was developed to categorise the LMC in a way which facilitates land morphology mapping at the national level. There has been no previous attempt in Portugal to map the mainland's land morphology at a 25 m spatial resolution**.**

4.4.1 Mapping criteria

The LMM method relates physical characteristics of landscape, through criteria that distinguish (1) slope gradient, (2) hydrological features and (3) surface curvature. This method can thus be used to identify wet (concave) and dry (convex) systems.

The mapping process for the construction of mainland Portugal's land morphology map is undertaken in ArcGIS 10.0 ESRI® and is based on the following data (i) 25 m resolution digital terrain model (INAG, 2010) (ii) INAG's (2010a) hydrological network map and INAG's (2010b) watersheds map at 1:25 000 scale (iii) water bodies and wetlands classes from the Portuguese land use/cover map (IGP, 2010).

(1) Slope gradient

Different authors describe flat areas with different upper slope limits (Table 4.1). Such limits depend on the research objectives, geomorphological characteristics and mapping scale. In the present work, the upper slope limit of flat areas that best represents the landscape in mainland Portugal is 5 %. Below this value, and the resulting map does not have sufficient detail, nor does it identify all floodplains. If the value is above 6 % ArcGIS over-compensates (Figure 4.3). The choice of upper slope limit was confirmed by comparisons with satellite images available at ESRI Base Maps® and land morphology maps drawn at the local scale (Figure 4.3a and Figure 4.3b).

Table 4.1 Upper slope limits from different authors

Upper slope limit of flat areas	Authors
< 8 %	Hammond (1954), Dikau (1989), Barka et al. (2011)
< 5 %	Dessaunettes et al. (1971), Saadat et al. (2008)
< 4 %	Brabyn (1998), Martins et al. (2013)
< 3 %	Speight (1990), Metternicht et al. (2005), Klingseisen et al. (2007), Wysocki et al. (2011)
< 2 %	Alexandre and Silva (2009)
< 2 º	Drăguţ and Blaschke (2006)
< 3 º	Reuter et al. (2006)
< 4 º	MacMillan and Shary (2009)
< 5 º	Giles (1998)

Once the national slope map was created (Figure 4.2b), its data was re-classified into two classes (Figure 4.3). The first corresponded to flat areas (< 5 %) and the second to non-flat areas (> 5%). The first class covers 30 % of mainland Portugal's area.

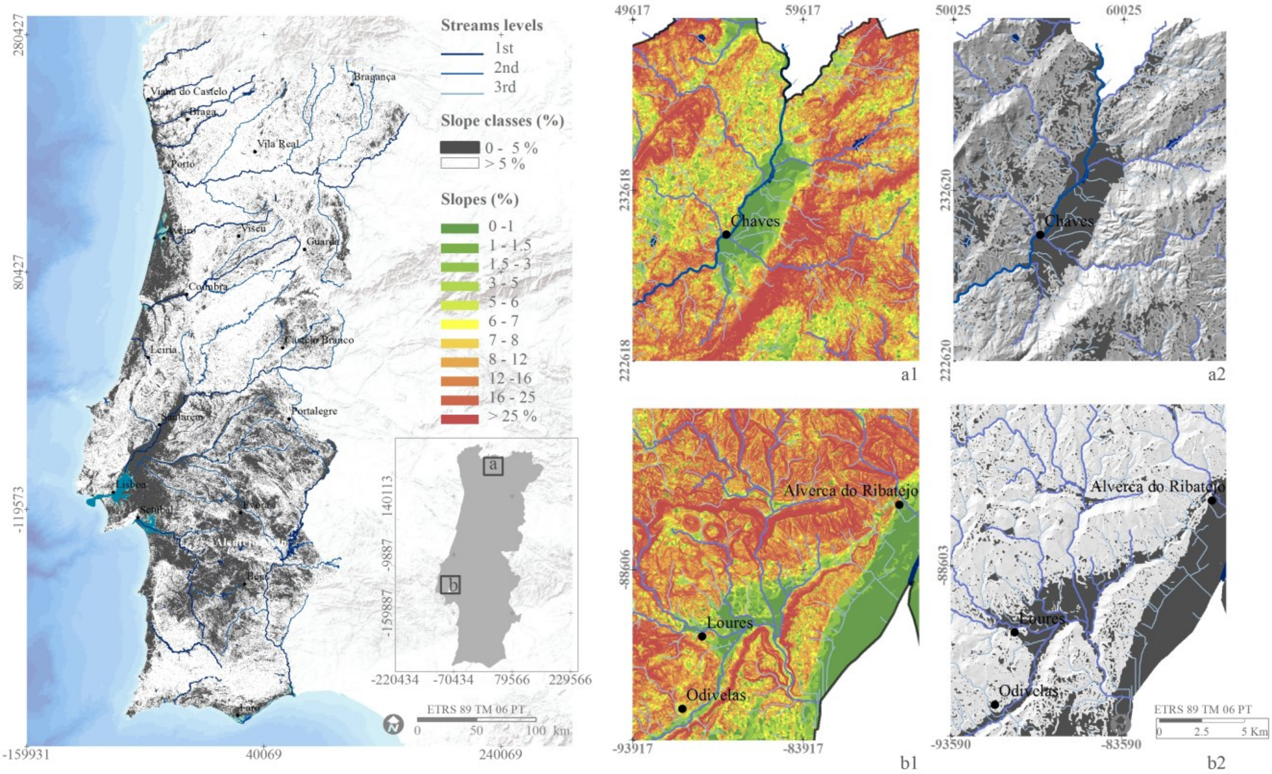

Figure 4.3 Flat areas for Portugal, slope < 5 %. Detailed slope maps (a) Veiga Chaves and (b) Várzea Loures.

(2) Hydrological network

The hydrological network outlines surface water flow across the landscape and includes streams and ridgelines in a hierarchical network. For mainland Portugal's stream network, a hydrological map derived from INAG (2010a) and hierarchized by Silva et al. (2013) was used. In Figure 4.4a streams are ranked into four levels according to their watershed size and stream length.

The ridgeline network depicted in Figure 4.4b was obtained through INAG (2010b) after the following procedure was applied (i) conversion of the closed watershed boundaries raster file into a line feature polygon; (ii) elimination of ridgelines inside the hypsometric class of 10 m above sea level; (iii) elimination of the lines within water bodies; (iv) elimination of ridgelines within 250 m of an intersection point with streams. This distance was chosen via a trial and error procedure by incrementing by 50 m each time; (v) ranking of the ridgelines into four levels according to the stream rank.

The LMM results depend on the mapping resolution, since the density and location of streams and ridgelines permit the identification and representation of the landforms in a more accurate way. If they are absent, valley bottom and hilltop recognition is not possible.

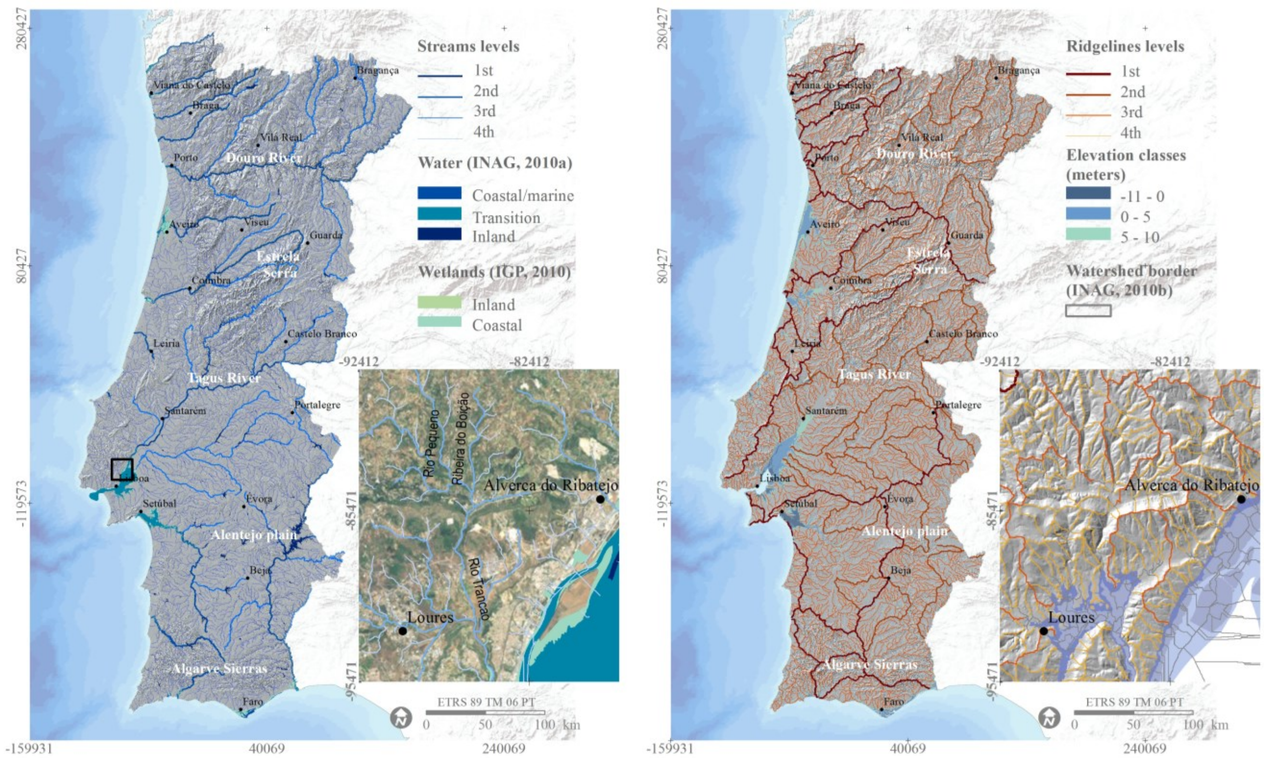

Figure 4.4 Portugal hydrological network (a) Streams map (Silva et al., 2013) and (b) Ridgelines map (based on INAG, 2010b), both with four levels at 1: 25 000 scale.

(3) Surface curvature

Surface curvature, also referred to as topographic convergence (Dietrich et al., 2003; Romstad and Etzelmüller, 2012; Wilson and Gallant, 2000) or local convexity (Evans and Cox, 1999; Evans et al., 2014; Iwashi and Pike, 2007), describes convexity and concavity of a terrain surface (Blaszczynski, 1997). Surface curvature is a local property that can calculate small variabilities in the hillslope profile, since it affects small scale landform types, due to its influence on water flow direction and infiltration (Evans and Cox, 1999). As the mapping community uses different terms to identify surface curvature they define different concepts and employ various methods to map it.

Slope gradient cannot be an absolute measure of land surface spatial configuration, since it doesn't reveal small variabilities in the hillslope profile. According to Wilson and Gallant (2000), tangential curvature is the best measure for calculating surface curvature. However, in ArcGIS 10.0 ESRI® this function produces significant noise and systematic errors, especially in flat areas. Consequently, in this work the concave-convex boundary is calculated through the cost allocation function, which combines slope gradient with the hydrological network. This function identifies and aggregates an area, or a cost surface, based on least effort or accumulative cost required to travel between two points. It thus identifies an inflection area where concavity changes (from down to up or up to down). In Figure 4.5a, the allocation areas result from the distance of moving either up or down a slope surface located between streams and ridgelines. In Figure 4.5b the areas identified represent the allocation areas only in slopes < 5 %.

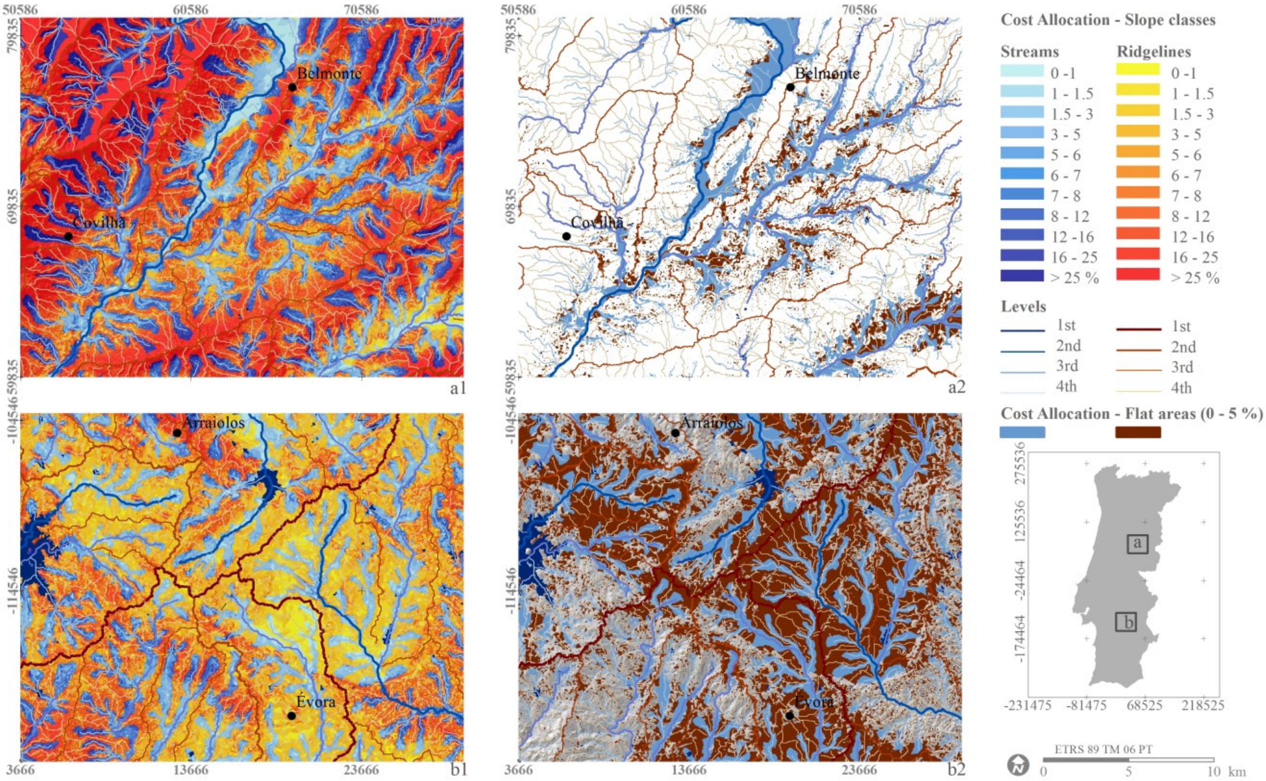

Figure 4.5 Cost allocation areas according to a) all slope classes and b) slope 0-5 %, (1) Covilhã-Belmonte and (2) Évora (25 m spatial resolution).

4.4.2 Land morphology mapping method

In this work, landforms are quantitatively categorised using the land morphology concept (LMC) and mapped using the land morphology mapping (LMM) method. The LMC and its classification of landforms is derived from the intersection of slope gradient, surface curvature and hydrological features. Although the following criteria is applicable to the Portuguese situation, it can be applied internationally, just by modifying the slope gradient relative to local conditions:

(i) Slope > 5 % where slopes > 25 % are identified as steep hillslopes.

(ii) Slope < 5 % that does not contain streams or ridgelines.

(iii) Slope < 5 % that contains either only streams or only ridgelines.

(iv) Slope < 5 % that contains both streams and ridgelines in the same polygon.

Areas (i) and (ii) are classified as hillslopes. Areas (iii) are classified as valley bottoms, if they contain streams and are classified as hilltops, if they contain ridgelines. Areas (iv) are complex because they are where the hillslope is absent and where flat areas may be either valley bottoms (concave) or hilltops (convex). Figure 4.6 shows the relation between them.

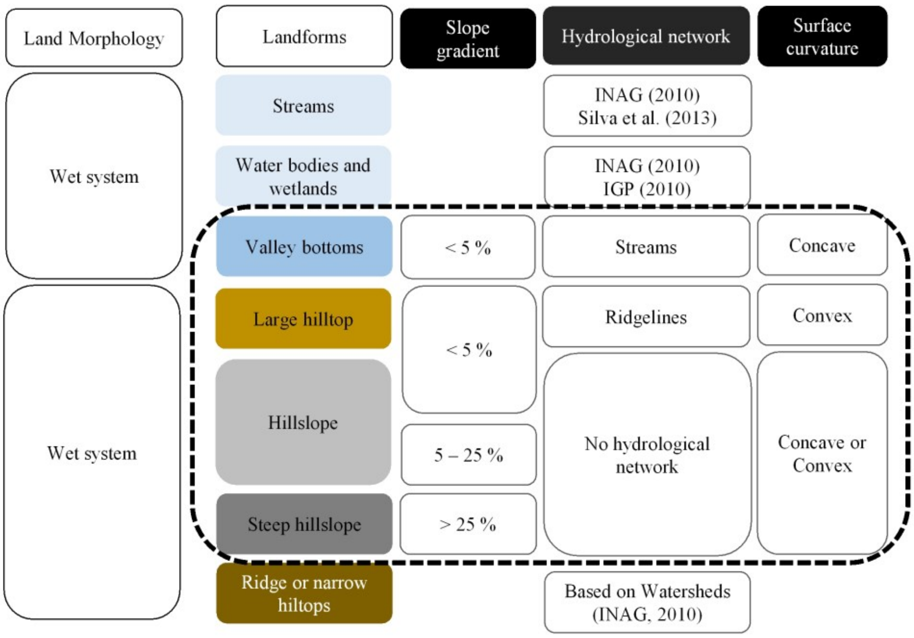

Figure 4.6 Dashed square identifies the features of the land morphology mapping (LMM) method.

The automatic landform classifications, MoRAP's and TPI, will be used to validate the criteria and the mapping method, specifically the flat areas with a concave-convex slope profile. Also the distribution of soils from wetlands will be compared with the land morphology map.

4.5 | Results

In this section, the usefulness of the LMM method is analysed for mainland Portugal, and the technique is compared with two automatic landform classifications: Topographic Position Landforms (TPI) and Missouri Resource Assessment Partnership (MoRAP) methods.

4.5.1 Land morphology mapping

The LMM method successfully created a GIS land morphology map, at 25 m spatial resolution, for mainland Portugal, which did not exist previously. Thus, Figure 4.7 represents Portugal's heterogeneous landscape by accurately depicting the wet and dry systems and showing a functionally interrelated connection between topographic and hydrological features. Consequently, the small variability of the hillslope profile can be identified, as shown in the land morphology map in Figure 4.8 (detail a4) and Figure 4.9 (detail b4)**.** Both figures show elevation and slope, along with the land morphology map contrasted against a site photo. All were drawn at the same scale**.** Figure 4.8 details the enclosed valleys bottoms with abrupt and extensive hillslopes that dominate in the North. In

Figure 4.9 with the elevation map the area is identified as lowland and with the slope map the area is identified as a flat area. With the addition of the land morphology map, the gently waved relief landscape located at south of the River Tagus can be seen with detail (Alentejo plain including Évora and Beja).

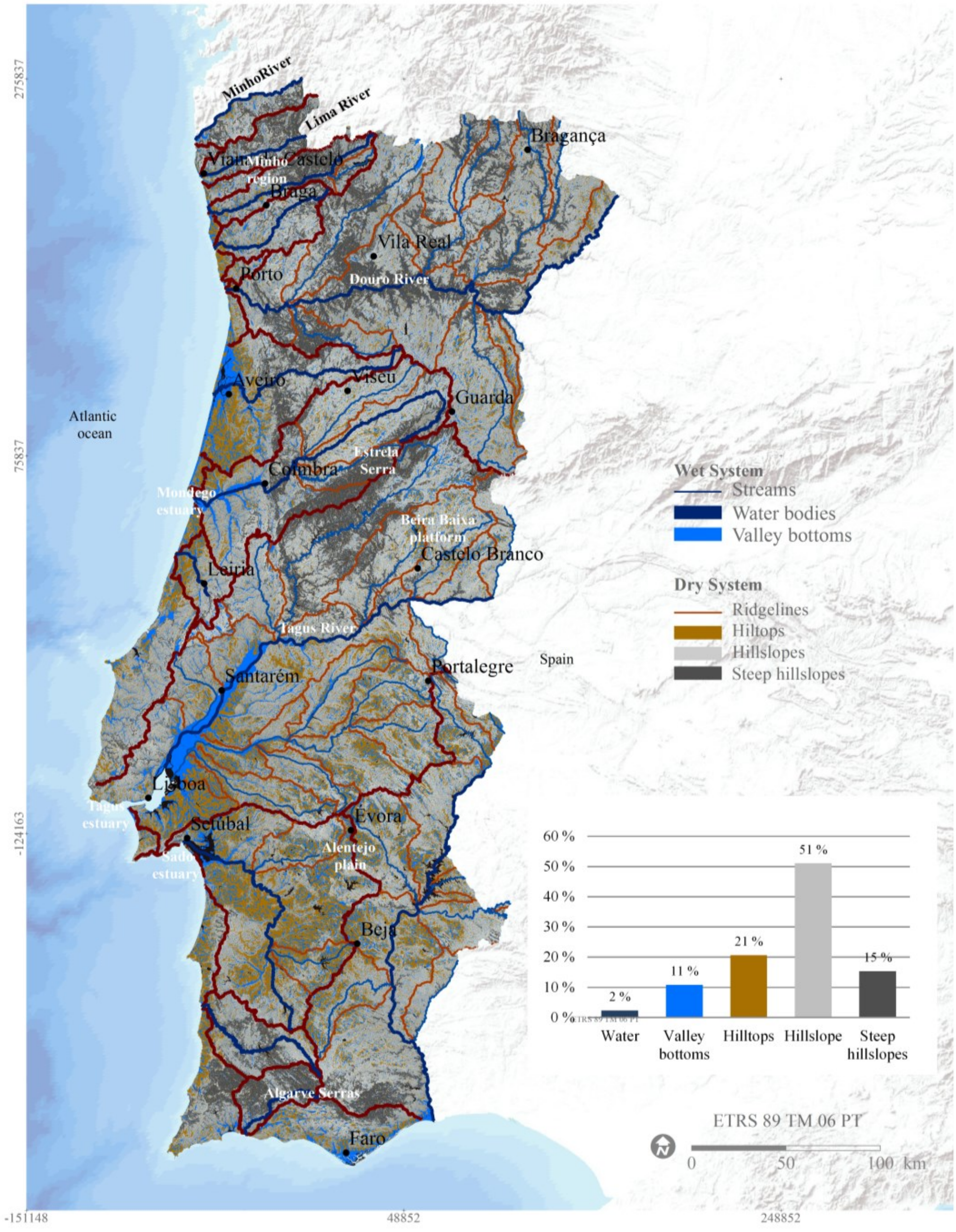

Figure 4.7 Land morphology in mainland Portugal

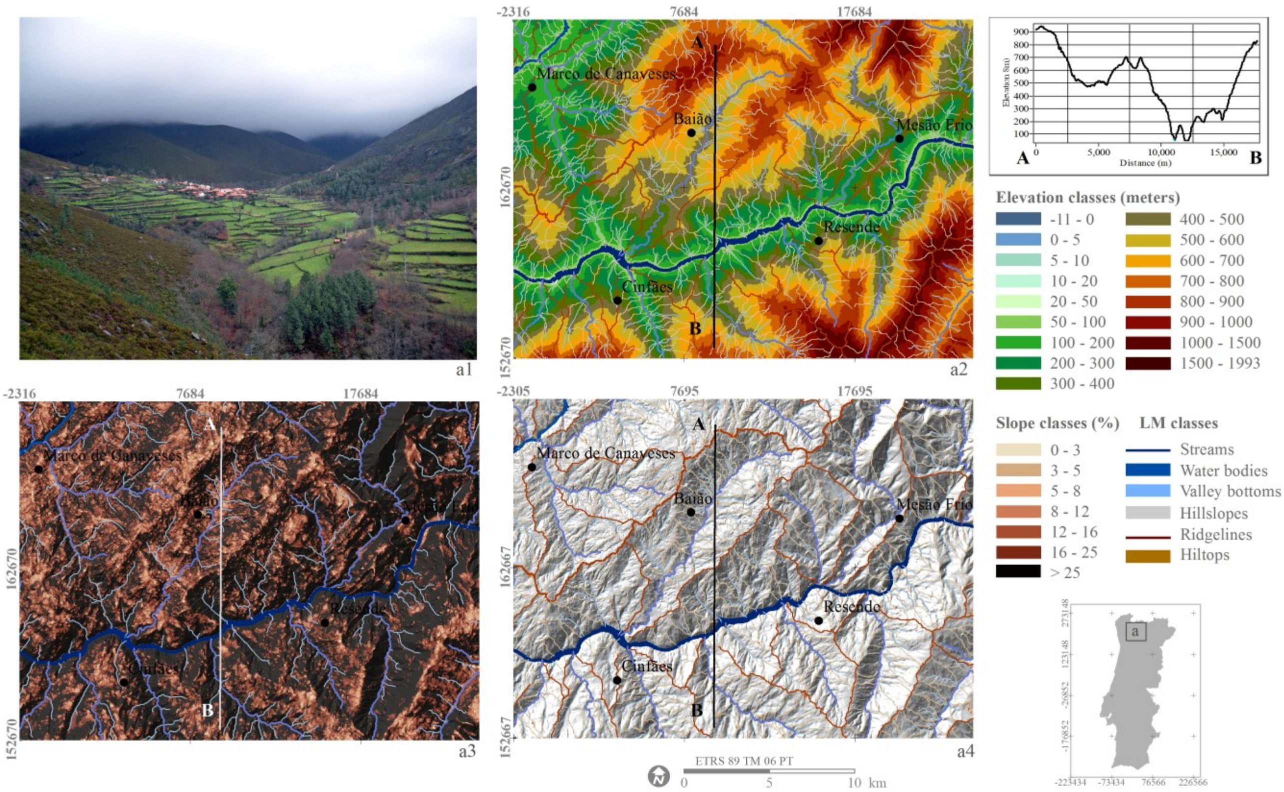

Figure 4.8 Detailed maps of enclosed valleys and extensive hillslopes in North region (1) site photo (2) hypsometric map (3) slope map (4) land morphology map.

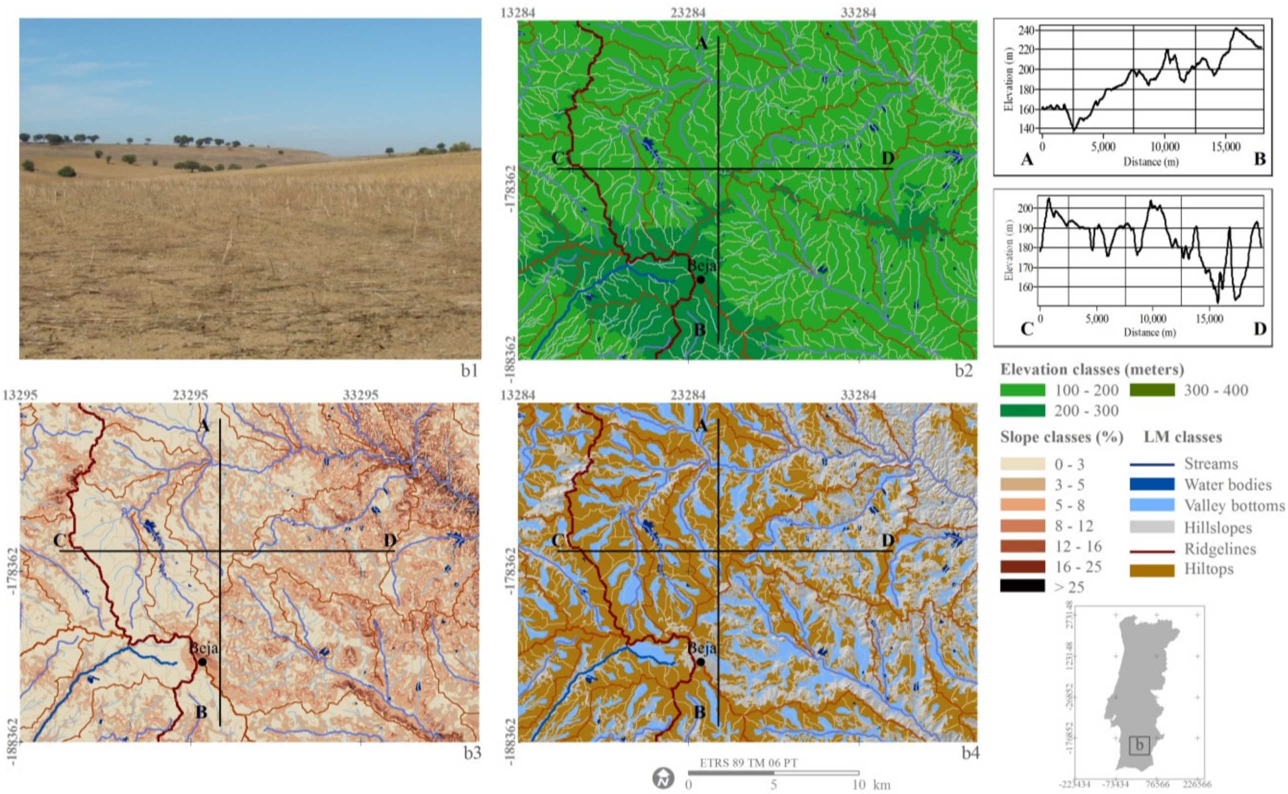

Figure 4.9 Detailed maps of gently waved relief in South Alentejo plain (1) site photo (2) hypsometric map (3) slope map (4) land morphology map.

4.5.2 Soils from wetlands map

There is no standardised national soil map for mainland Portugal. SPCS (2004) and Gonçalves et al. (2008) recognise that Portuguese soil data is limited to regional maps drawn at various scales, using different soil taxonomies and field methodologies (i) SROA - Serviço de Reconhecimento e Ordenamento Agrário from Portugal (Cardoso et al., 1973) and (ii) WRB - World Reference base (FAO, 1988; FAO, 2014). Leitão et al. (2013) digitalised a national soil map who attempted to compile and homogenise soil local data so that a national map could be pieced together. The problem is that there is no unified scale resulting in polygon mismatches when one tries to map features in ArcGIS.

Whilst the WRB has mapped certain areas of mainland Portugal, gaps remain, which are filled by older localised maps, drawn by SROA (e.g. 1965; 1974) who defined soils using a Portuguese classification system not recognised by the international community. For example, the SROA maps have the following soil classes Recent Alluvisols, Ancient Alluvisols, Colluvisols and Organic Hydromorphic Soils, which correspond to what the WRB recognises as Fluvisols, albeit with some minor differences. Consequently, the two soil classifications (WRB and SROA) were cross-referenced to identify commonalities between the referred classes. Once this was done one umbrella class could be created, which encompasses both systems. This was called soils from the wet system. With the umbrella class established, a provisional map could be created, piecing together the different scales, 1:100 000 for the North and 1:50 000 for the South, and were able to compare and contrast with Figure 4.7.

As seen in Figure 4.10 and 4.10a**,** there is a link between soils and the wet system, with almost 67 % of Recent Alluvisols *i.e*. those soils developed on holocenic alluvions, located in valley bottoms and 9 % in wetlands (a). Thirty-five percent of these soils are also located in the 0–1 % slope areas and 80 % in the 0–5 % slope areas (Figure 4.10b).This distribution corroborates the statement that fertile soils are found typically on river floodplains, wetlands, valleys and in coastal lowlands (FAO, 2001). However 18 % of these soils are located in hillslopes, and since Fluvisols/Alluvisols developed on alluvial deposits, this suggests that they may not have been well mapped.

Regarding Ancient Alluvisols, *i.e.* those soils developed on materials from river terraces dated from Pleistocene, 77 % are located in flat areas, and frequently found in the slope class 1–2 % (23 %) (Figure 4.10b and c). Unlike recent Alluvisols that are mostly represented in the wet system, ancient Alluvisols are spread across the wet and dry system.

Colluvisols are more frequently found (44 %) on slopes between 2–5 % but they also appear in 38 % of the slopes between 5 and 12 %. This validates their colluvium origin, which depends on the transport and accumulation of materials into the hillslopes base, valleys or depressions. The other types of soils are represented on all slope classes.

Figure 4.10d shows that 68 % of valley bottoms do not correspond to soil types from wetlands. As a result it can now be stated that the valley bottom boundary should not be defined only by the presence of Fluvisols, as they have been commonly mapped in landscape plans.

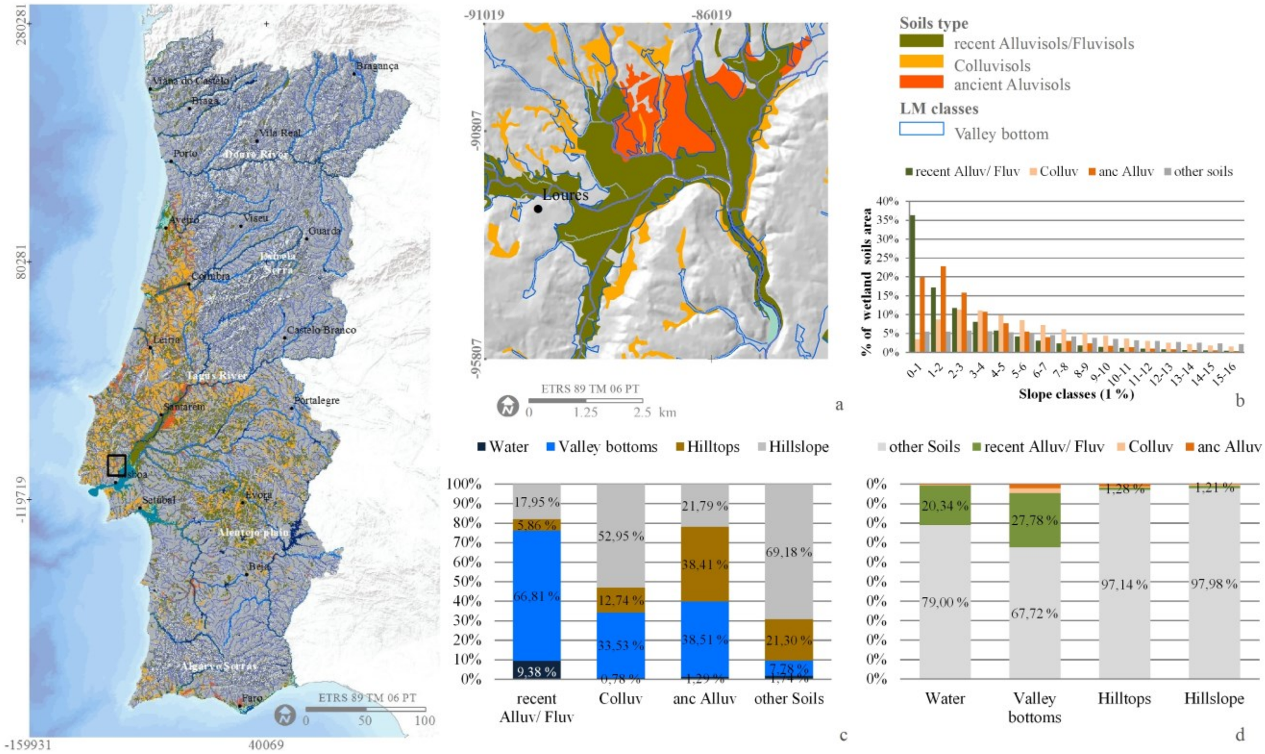

Figure 4.10 Soils from wetlands map for mainland Portugal (based on Leitão et al. 2013) (a) detail from Loures Várzea (b) wetland soils distribution according to slope classes (c) wetland soil distribution according to LM classes (d) LM classes distribution according to wetland soils.

4.5.3 Automatic landform classifications - TPI and MoRAP

The LMM method is contextualised according to both topological and hydrological classifications. Therefore the results are compared to the classes established by the TPI and MoRAP methods.

As stated in the introduction, the TPI map is composed of two levels, slope position and landform category. Portugal's slope position map is shown in Figure 4.11a and is similar to Portugal's landform category map. This map indicates that mainland Portugal is mainly composed of flat slope and middle slope areas, which collectively correspond to almost 57 % of its area. The flat slope category corresponds to 37 % and is labelled as a single landform. In the LMM method however, slope gradient is an input criteria used to define landforms and is not a landform in its own right. Flat areas within the LMM method are those areas with a slope between 0 and 5 %. They are classed as either valley bottoms, hillslopes or hilltops. The exact class depends on the hydrological network and surface curvature.

It is important to note that the valleys, as defined in the TPI, do not correspond to the valley bottoms of the LMM method. Likewise, ridges do not correspond to ridgelines and hilltops. In fact, 85 % of TPI's valleys and 90 % of its ridges are hillslopes (Figure 4.11b). Equally, the TPI model labels flat slope, the LMM categorises as valley bottom (23%), hillslope (30 %) and hilltop (43 %). The difference comes from the fact that TPI does not map landforms relative to the hydrological network. Instead, it maps a valley or ridge according to the respective lowest and highest elevation points within a neighbourhood. This does not reflect the morphological reality and therefore does not depict well the Portuguese landscape. In fact, the TPI ignores the small topographic differences in the landscape, as is confirmed by De Reu et al. (2013). For this reason, LMM method is an improved operating method which distinguishes two very different ecologically landforms.

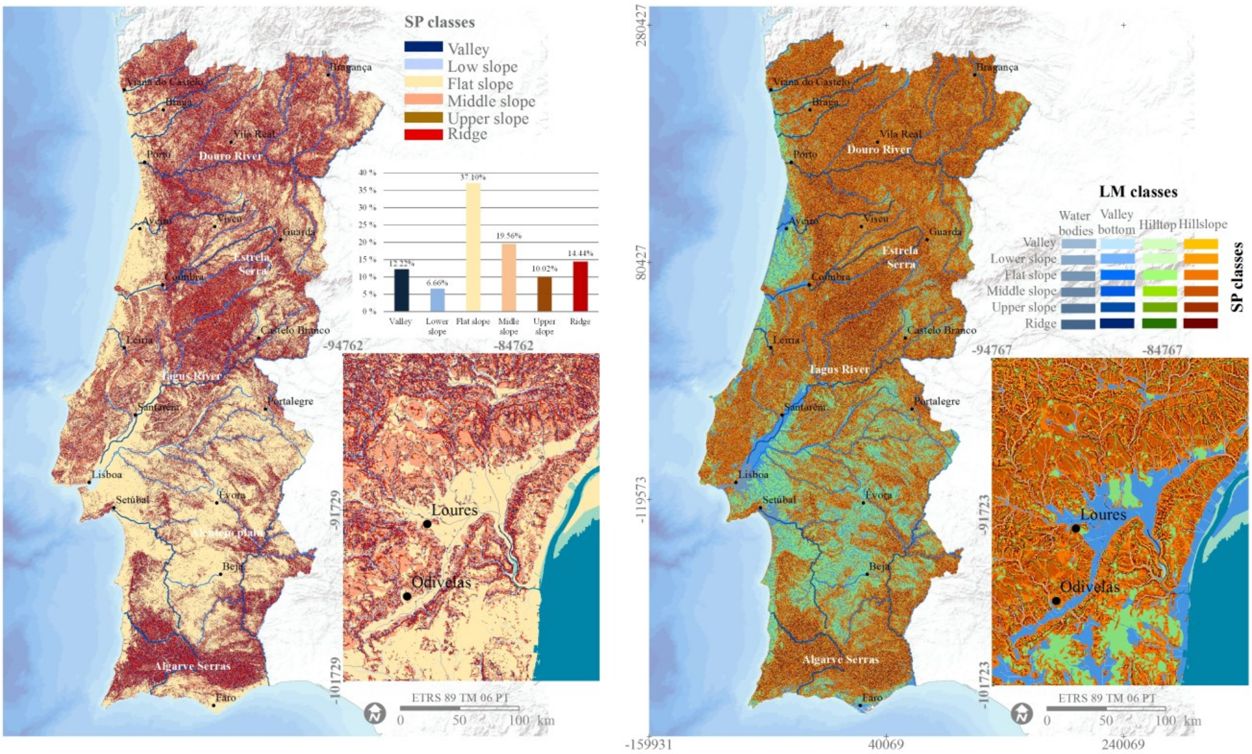

Figure 4.11 TPI method application to mainland Portugal (a) Slope position map and (b) Comparison between SP and LM maps.

The other automatic classification used in the comparison is MoRAP's (True, 2002). Portugal's landform map taken directly from Sayre et al. (2014) global ecological land units, is shown in Figure 4.12. This map identifies 50 % of mainland Portugal as flat plains which corresponds to a slope < 8 %

and a relative height relief between 1–15 m and smooth plains where the slope is < 8 % and the relative height relief is between 16–30 m.

The MoRAP classification is topological, and therefore characterizes landforms based on two parameters: slope and relief. Figure 4.12b shows that MoRAP classification is correct. The main difference is that flat plains are labelled as a single landform. The main differences and tension points are similar to those analysed for the TPI method and relate to the fact that LMM uses slope as an input.

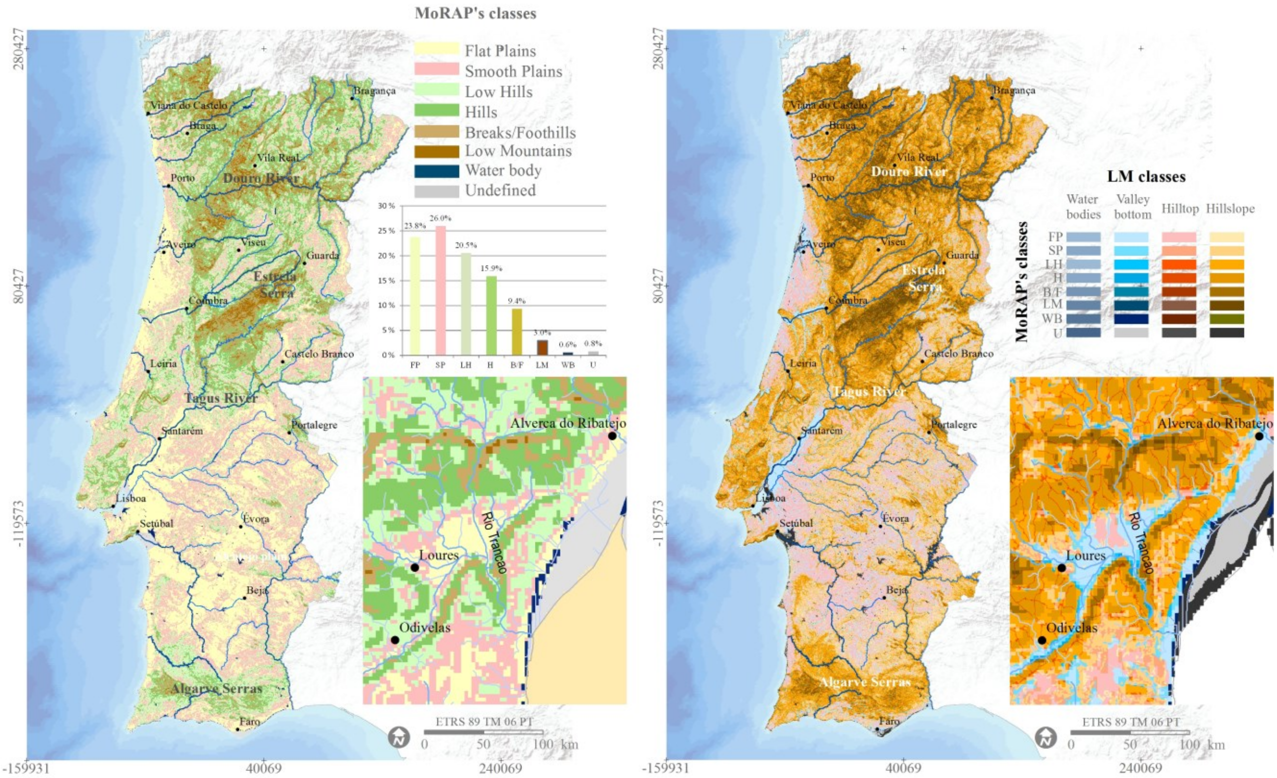

Figure 4.12 MoRAP method application to mainland Portugal (a) MoRAP’s landform map based on the 250 m DEM resolution (USGS GMTED2010). A circular 1 km2 neighbourhood analysis window was used (b) Comparison between MoRAP’s and LM maps.

4.6 | Discussion

Throughout the development of the LMC and LMM beginning in Magalhães (1993) and extending to Magalhães (2001), the concept and mapping method have been not clearly defined, leading to the boundaries between them being blurred. This has resulted in a certain level of confusion and limited application/communication, which does not reflect the usefulness or value of the method. In certain instances, the landforms have not been referred to by the most commonly used terms within the wider mapping community. The main problem, however, was the interchangeable and indiscriminate use of the term land morphology to describe the land morphology concept. The concept provides a means to classify land morphology (systems) and landforms elements, and does not refer to the landforms or land morphology *per se*. Hence, the recognition as to the need to separate the two terms land morphology and land morphology concept. It is also important to clearly divide the theoretical LMC from the mapping method (LMM) it establishes. Consequently, LMC and LMM clarification should support the use of the concept and method outside of the "Lisbon School".

As a result of this clarification, the LMM method is a helpful evaluation tool for modelling natural systems across regions and countries (simply by modifying slope gradient). It could be used to solve the mapping issues when the hillslope is absent, as identified in Dietrich and Perron (2006) and Hugget (2011). Both LMM and LMC can be applied on a national scale, with sufficient detail to capture finer landforms details at the local scale, since each landform mapped is characterised by different land surface parameters, relative to surface water flow and accumulation, microclimate, soil erosion and vegetation. The LMM is robust enough to support environmental and planning authorities to take decisions based on a more thorough analysis of the land value and its ecological functions. The LMC and LMM may, therefore, contribute to the MoRAP database and by extension enhance the global land ecological unit map (Sayre et al., 2014), by adding information about ecological services in the wet and dry system (Table 4.2).

Table 4.2 Relation between LMC and ecological functions.

Land morphology	Physical			Biological	Cultural
	Water	Microclimate	Soil	Vegetation	Recreational
Wet system	Water accumulation Biogeochemical cycling Flood control Surface water storage and recharge	Temperature regulation Cold air accumulation and air drainage Local breezes (mountain/valley breezes)	Soils/sediments and nutrients accumulation	Wet associations Riparian vegetation Wildlife habitat Biodiversity	No building suitability
Dry system	Surface Runoff Infiltration and percolation Groundwater recharge Flood control (upstream)	Cold air formation (hilltop) Thermal belt (hillslope)	Soil erosion and nutrients leaching	Dry associations	Good building suitability (hillslope) Conditioned building suitability Soil erosion/protection (wind and water erosion on hilltops and steep hillslope)

As the entire wet system has been mapped for Portugal, floodplains and potential flood risk areas can be provisionally delimited, where there is no available hydrological data (Cunha et al., 2017). Also, by mapping and distinguishing hilltops, hillslopes and steep hillslopes, it can be more accurately stated suitable land uses, which will in turn decrease soil erosion. Figure 4.7 allows the mapping community to identify different types of landscape, such as the enclosed valley bottoms with abrupt and extensive hillslopes located on hard lithology at north of Tagus River and the gently waved relief of the south, namely in Alentejo plain. These details add to the information provided by Pereira et al. (2014) and can inform Portuguese land unit mapping, such as that published by Cancela d'Abreu et al. (2004). Furthermore, Table 4.2 and the LMM method support the Portuguese Ecological Network (Magalhães et al., 2013) as a planning tool to increase ecological connectivity, conserving and buffering core areas such as floodplains (Cunha et al., 2017) and modelling ecological suitability maps, *i.e.* urban, agricultural and forestry areas (Magalhães et al., 2015; Mesquita et al., 2015).

The obtained results also provided a quantitative way, through the comparison with the soil map compiled by Leitão et al. (2013), to interpret local dynamics/relationships between fertile soils, valley bottoms and alluvial floodplains, and less fertile soils with ridges and hillslopes. The results and analysis show that the valley bottom boundary should not be defined only by the presence of Fluvisols, which is an important consideration when the Portuguese Government decides to re-map soils. One important issue to note is that the Figure 4.7 provides evidence to show that the soils located in the Portuguese wet system may not have been correctly classified. This suggests that they should be re-mapped urgently with standardised WRB classification.

4.7 | Conclusion

The LMC and LMM application commonly defined terms used within the mapping community and standardized criteria was applied, which clarifies previous issues with the concept and methodology. This contributes to the mapping community because LMC and LMM provide a means to distinguish the wet and dry systems, by using slope gradient and hydrological features as an input criteria to define landforms, unlike the TPI and MoRAP where slope is considered as a landform *per se* (termed flat area for example). Therefore, this methodology is valuable complementary tool to TPI method and MoRAP database.

The LMM method is thus a helpful evaluation tool for modelling natural systems across regions and countries (simply by modifying slope gradient). By specifically distinguishing valley bottoms and hilltops from flat areas, an atypical practice in landform classification, the LMC and LMM method can delimit floodplains, and give information about flood risk in areas, where there is currently no or poorly available hydrological data. Furthermore, it was shown that LMM is robust enough to support environmental and planning authorities in taking decisions based on a more thorough analysis of land value and ecological functions. This method could be used to solve the mapping issues that occur when the hillslope is absent. Specifically for the Portuguese case, the LMC and LMM were employed to create a 25 m spatial resolution GIS map of mainland Portugal's land morphology systems and landform elements. The map was produced through the selection of slopes of < 5 %, as a specific criterion to mainland Portugal. The mapping of concave-convex surfaces was undertaken relative to the hydrological network. Cartographic details at this level of scale did not exist previously for Portugal, so this represents an important innovation to the mapping community and fills in knowledge gaps for both the Portuguese Government and the European Union.

In the future, the land morphology map and data can be used in combination with the Portuguese land units to redefine ecological land units and to map ecosystems and their services more accurately. Finally, and given its contribution to the identification and mapping of soils from the wet system, this work also supports existing calls as to the need for a new soil map for Portugal, drawn according to the standardised WRB classification.

4.8 | References

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4.9 | Supplementary material

Table S4.1 Landform classifications - Physically based methods

Authors	Geometric signature— variables	Classification groups
Wood (1942)	Slope – A system developed for mountain slopes	Four unit slope model - upper convex segment, cliff face, straight segment and lower concave segment.
Hammond (1954, 1964a, 1964b)	Percentage in 8% slope gradient, local relief and profile type	Plains: Flat or nearly, Smooth plains with some local relief, Irregular plains with slight relief, Irregular plains with moderate relief; Tablelands: with moderate relief, considerable relief, high relief, very high relief; Plains with hills or mountains: plains with hills, plains with high hills, plains with low mountains, plains with high mountains; Open hills and Mountains: open low hills, open hills, open high hills, open low mountains, open high mountains; Hills and Mountains: hills, low hills, high hills, low mountains, high mountains;
Thrower (1960)	Percentage of land in gentle slope (< 8 %) and relative local relief	4 Terrain types - mountains, hills, rolling and irregular plains, nearly level plains
Dalrymple et al. (1968); Conacher and Dalrymple (1977)	Relative position, slope, profile curvature and actual processes	Nine-unit slope model - interfluve (0–1° slope gradient), seepage slope, convex creep slope, fall face, transportational midslope, colluvial footslope, alluvial toeslope (0–4°), channel wall and channel bed
Ruhe and Walker (1968) in Wysocki et al. (2011)	Slope gradient, slope length, slope width and curvature	Hillslope was divide into five segments: summit, shoulder, backslope, foot slope, toe slope and alluvium. Also identified geomorphic units of head slope, nose slope and side slope
Desaunettes et al. (1971)	Slope and elevation range	River alluvial plains (< 1 %), piedmont plains (< 5 %), gravelly talus fans, gravelly river fans, plateau and upper terraces, hills (mostly 8–25 % and 50–500 m), mountains (> 25 % and > 100 m, mostly 500-1500 m), lowlands (< 1 %)
Canada Soil Survey Committee (1976)	Two basic attributes: 1) Materials - unconsolidated mineral and organic components; and 2) Surface expression or form – according to assemblage of slopes, primary depositional form and modifying processes	Map units according to Slope - Level, nearly level, very gentle slopes, gentle slopes, moderate slopes, strong slopes, very strong slopes, extreme slopes, steep slopes, very steep slopes. This system is conceptual in scope and is not parametric because it generally lacks precise limits on the boundaries between classes.
Speight (1974, 1990)	Slope, topographic position, dimensions, geomorphological activity and agent	9 types of topographic - Crest, depression (open, closed), flat (< 3 % slope), simple slope, upper slope, mid slope, lower slope, hillock, ridge. 40 types of landform patterns including, e.g., floodplain, dune field and hills and more than 70 types of landform elements such as cliff, footslope and valley flat.
Pennock et al. (1987)	Slope gradient, plan and profile curvatures	9 three-dimensional hillslope model: convergent, planar and divergent: shoulders, backslopes and footslopes, and level terrain.

Table S1 Landform classifications – Physically based methods (cont.)

Authors	Geometric signature— variables	Classification groups
Dikau (1989) Dikau et al. (1991, 1995)	Percentage in 8% slope gradient, local relief, profile type	96 possible subclasses, aggregated into 24 mapped classes and 5 main types
Dietrich et al. (1993)	Hydrological network	TOPOG model - Based on Montgomery and Dietrich (1989) to predict the pattern of channelization.
Irvin et al. (1997)	Elevation, slope, incident solar radiation (aspect), profile curvature, tangent curvature and wetness index	Unsupervised clustering - 8, 10, and 12 classes or continuous (fuzzy) - 14 classes
Blaszczynski (1997)	Local elevation, convexity	Concave and convex areas, crests and troughs, enclose basins, sloping flats, and horizontal flats
Brabyn (1998)	Percentage in 4% slope gradient, local relief, profile type	Uses Dikau (1989) classes but classified flat areas if it is less than 4%
Burrough et al. (2000)	Elevation, slope, profile and plan curvature, mean wetness index, ridge proximity and annual irradiation	Fuzzy k-means - Topological drainage nets - understanding of how the landscape functions.
MacMillan and Pettapiece (1997) MacMillan et al. (2000, 2004), MacMillan and Shary (2009)	Slope gradient, profile and plan curvatures, wetness index, %Z relative to min and max elevation, % Z relative to local pits and peaks, absolute maximum pit and peak relief, % Z relative to nearest stream and divide, absolute height (Z) above local pit cell	LandMap R – Fifteen landform units.
Magalhães (2001)	Slope and hydrological network	Manual method – Wet and dry system
Meybeck et al. (2001)	Relief roughness and mean elevation	15 relief patterns - plains, mid-altitude plains, high-altitude plains, lowlands, rugged lowlands, platforms, low plateaus, mid-altitude plateaus, high plateaus, very high plateaus, hills, low mountains, mid-altitude mountains, high mountains, very high mountain
Weiss (2001)	Elevation and mean elevation, with hydrological and drainage networks	Landform classes - canyons, deeply incised streams, midslope drainages, shallow valleys, upland drainages, headwaters, U-shaped valleys, plains small, open slopes, upper slopes, mesas, local ridges/hills in valleys, midslope ridges, small hills in plains, mountain tops, high ridges
Pennock and Corre (2001), Pennock (2003)	Elevation, relief, gradient aspect, profile and plan curvatures, slope length	Landform segmentation, and soil redistribution - upper level, shoulder, backslope, footslope
True (2002)	Slope and local relief	MORAP - Missouri Resource Assessment Partnership
Morgan and Lesh (2005)	8% slope gradient, local relief and profile type	reprogrammed Hammond's method using ESRI's Model Builder
Metternicht et al. (2005), Klingseisen et al. (2007)	Slope, local relief, elevation percentile, elevation, curvature	LANDFORM software - Morphological type (topographic position) classes by Speight (1990) – Crest, simple slope, flat, depression
Gallant et al. (2005)	Percentage in 8% slope gradient, local relief, profile type	Mapping Hammond's landforms
Jenness (2006)	Slope direction (aspect), slope position, slope shape (planform curvature), topographic moisture index and stream power index	Based on Weiss (2001) classes

Table S1 Landform classifications – Physically based methods (cont.)

Authors	Geometric signature— variables	Classification groups
Prima et al. (2006)	Slope, aspect, convexity and concavity	Landform types - volcanoes, alluvial fans, alluvial plains, mountains and hills
Drăgut and Blaschk (2006)	Elevation, profile curvature, plan curvature and slope gradient, image segmentation	Peak, shoulder, steep slope, flat or gentle slope, side slope, nose slope, head slope, negative contact, toeslope
Iwahashi and Pike (2007)	Slope gradient, Surface texture, local convexity	Combination of threshold - 8, 12 and 16 http://gisstar.gsi.go.jp/terrain/front_page.htm.
Barringer et al. (2008)	Local geometry (curvature and slope) and landscape context	S-map New Zealand's soil database
Saadat et al. (2008)	Slope, elevation range, stream network pattern and ASTER image	Landform types - River alluvial plains, piedmont plains, gravelly talus fans, gravelly river fans, plateaus, upper terraces, river terraces, hills and mountains
Gerçek (2010)	Slope, curvature, local elevation, TPI, Surface flow and proximity to terrain network	Fuzzy geomorphometric classes - Planar slope, foot slope, channel, ridge, shoulder, hollow, spur, plain, peak, hollow shoulder, saddle nose, hollow foot, spur foot, pit
Evans (2012)	Altitude, slope, curvature and flow network	Extensive plains and highly irregular topographies, among others
Drăguţ and Eisank (2012)	Elevation and standard deviation of elevation	Classification was used in the first object-based classification of Earth's topography - High mountains, low mountains, high hills, tablelands, rough hills, smooth hills, irregular plains, flat plains
Jasiewicz and Stepinski (2013)	Elevation - zenith or nadir angles and relief threshold	Landform elements or geomorphons - From the possible 498 different landform types, the method establishes a finite, absolute set of possible landforms
De Reu et al. (2013)	Elevation and mean elevation, with hydrological and drainage networks	Based on Wilson and Gallant (2000) and Weiss (2001)

5 | THE LAND MORPHOLOGY APPROACH TO FLOOD RISK MAPPING: AN APPLICATION TO PORTUGAL

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5 | THE LAND MORPHOLOGY APPROACH TO FLOOD RISK MAPPING: AN APPLICATION TO PORTUGAL

Abstract

In the last decades, the increasing vulnerability of floodplains is linked to societal changes such as population density growth, land use changes, water use patterns, among other factors. Land morphology directly influences surface water flow, transport of sediments, soil genesis, local climate and vegetation distribution. Therefore, the land morphology, the land used and management directly influences flood risks genesis. However, attention is not always given to the underlying geomorphological and ecological processes that influence the dynamic of rivers and their floodplains.

Floodplains are considered a part of a larger system called Wet System (WS). The WS includes permanent and temporary streams, water bodies, wetlands and valley bottoms. Valley bottom is a broad concept which comprehends not only floodplains but also flat and concave areas, contiguous to streams, in which slope is less than 5 %. This will be addressed through a consistent method based on a land morphology approach that classifies landforms according to their hydrological position in the watershed. This method is based on flat areas (slopes less than 5 %), surface curvature and hydrological features.

The comparison between WS and flood risk data from the Portuguese Environmental Agency for the main rivers of mainland Portugal showed that in downstream areas of watersheds, valley bottoms are coincident with floodplains modelled by hydrological methods. Mapping WS has a particular interest in analysing river ecosystems position and function in the landscape, from upstream to downstream areas in the watershed. This morphological approach is less demanding data and time-consuming than hydrological methods and can be used as the preliminary delimitation of floodplains and potential flood risk areas in situations where there is no hydrological data available.

The results were also compared with the land use/cover map at a national level and detailed in Trancão river basin, located in Lisbon metropolitan area, an urbanized basin that suffered heavy flooding in the last decades. This study also contributes to a better understanding of the basin morphology at a local-scale and the effects of soil sealing in downstream flood risks.

This work will contribute to the understanding of the morphology, ecology and land use of watersheds that could be used to reduce runoff and downstream flood risk. This can be accomplished by using natural water retention and infiltration methods or higher-level based planning instead of a reaction to local decisions on flood hazards. This morphological approach to map landforms, including wet system, is a valuable tool to assist policy makers and planners in flood risk and land use management,

floodplain restoration, agricultural land management practices, and location of human activities according to ecological suitability.

Research highlights

• Land morphology (LM) method consistently mapped all river ecosystems for Portugal.
• Valley bottoms coincide with floodplains in downstream areas of the watersheds.
• Easier and less demanding method to map floodplains at a large scale.
• LM approach is a complementary tool for land use planning and flood risk mapping.

Keywords •Wet system •Floodplains •Land morphology •Flood risk •Portugal •Trancão River basin.

5.1 | Introduction

Since ancient times, populations have settled near floodplains, taking advantage of their valuable geographical and biophysical conditions, e.g. fertile soils with high food productivity, navigable waterways, with access to water supplies for transportation and power development (Balica et al., 2009; Douben, 2006; OAS, 1991). The increasing vulnerability of these areas is linked to changes in population density and land use (Douben, 2006; EEA, 2013; EEA, 2015). In the same way, there is a direct relation between incorrect land use practices and flood risk and frequency (Deasy et al., 2014; Leopold, 1994; Zaharia et al., 2015). The dramatic increase in flood hazard is consequence of several activities that promote soil structure degradation, leading to soil erosion, decrease of water infiltration rates and water storage capacities (Wheater and Evans, 2009), increase of rapid runoff, stream flow increase and rising flood level (Brauman et al., 2007; Minea, 2013). The soil degradation is a consequence of soil sealing due to incorrect practices, either arable or grazing intensification as upland deforestation, intensive agriculture, or urbanization and construction of infrastructures (EEA, 2012; Jacinto et al., 2015; Minea, 2013; OAS, 1991; Wheater and Evans, 2009).

A higher-level planning based on land morphology and landforms mapping, including floodplains and flood risk areas, is an essential tool to reduce flooding and associated costs with damages and insurance claims. This approach could help to change the paradigm of urban location, in order to "keep the people away from floods" and should be incorporated into new maintenance strategies focus on "self-regulating nature" as "inclusive River management" (Fliervoet et al., 2013), "Room for River" (De Groot, 2014; Lennon et al., 2014; Rohde et al., 2006). Such measures have been encompassed by the 2000/60/EC Water Framework Directive (EC, 2000) and 2007/60/EC Floods Directive (EC, 2007) which were designed to identify hazard areas, and urban development that promotes soil sealing, especially in floodplains.

Mapping landforms is particularly useful for analysing river ecosystem position and function in the landscape. Land morphology is also a valuable complementary tool to assist policymakers and planners, not only in terms of flood risk, but also in land use management because it can identify ecological suitability areas for societal activities (Magalhães et al., 2007).

For any given scale, landforms can be quantitatively categorised and mapped, according to their hydrological position in the watershed, by using the land morphology concept (LMC) and land morphology mapping (LMM) method (Magalhães, 2001; Magalhães et al., 2007). By classifying landforms according to hydrological position, it also outlines two different systems, the wet and dry (concave-convex surfaces) in the hillslope profile, including valley bottoms, hilltops and hillslope. As a topographic and physical method, it recognises and maps, with sufficient detail, finer landforms characterised by different land surface parameters, relative to surface water flow and accumulation, microclimate, soil erosion and accumulation, and vegetation.

In this paper, the land morphology concept (LMC) approach is used to map Portuguese landforms. The authors thus evaluate how landform mapping, particularly when it comes to the wet system, can support flood risk management. The LMC is applied through the land morphology mapping (LMM) method, using mainland Portugal as the case study. The resulting land morphology map is based on the 25 m resolution DTM, and is derived from the intersecting of flat areas (slopes less than 5 %), surface curvature and hydrological features, including streams and ridgelines. The map for is compared and validated, at both the national and local scale, against previous flood risk data obtained from hydrological models for the main river basin. One set of data was taken from 2010 by the former National Water Institute (Instituto Nacional da Água – INAG, 2010) and the other from the 2015 database belonging to the Portuguese Environmental Agency (Agência Portuguesa de Ambiente – APA, 2015) and that of the 2010 land use and cover map from Portuguese Geographic Institute (Instituto Geográfico Português – IGP, 2010).

Given that hydrological modelling requires full documentation of hydrological characteristics and some streams are difficult to model, the LMC/LMM approach is a simplified one that does not affect the quality of the results. It is less demanding in terms of data, it is less time-consuming, and does not require so many complex steps. Consequently its introduction to mainstream flood mapping poses significant value for the Portuguese Government and the European Union, especially where there is no, or limited, available hydrological data for all river basins to map floodplains and flood risk areas.

5.2 | Floodplain and wet system mapping

Floodplains are a vital part of river ecosystems, providing a buffer between the river and human activities on land (Konrad, 2015; Naiman et al., 1993). A broad definition of the term "floodplain" is given by Schmudde (1968). It encompasses three criteria: (i) topographical – flat and adjacent area to a stream (ii) geomorphological – a landform composed primarily of unconsolidated depositional material derived from stream sediments, and (iii) hydrological – a landform subject to periodic flooding by a parent stream. A floodplain may also be defined as a relatively smooth area of land adjacent to a stream or river that naturally flow beyond their banks, every few years during periods of high discharge (Marriott and Alexander, 1999; Goudie, 2004; Junk et al., 1989; Leopold et al., 1964; OAS, 1991).

Since flooding is a naturally recurring event (Bayley, 1995; Leopold et al., 1964) it may also be used to define natural floodplain environments (flood pulse concept) (Junk et al., 1989). Consequently, the demarcation of flood risk/ flood-prone areas is based on floodplain delineation. In turn, a flood risk refers to the probability of a flood event causing adverse consequences to human health, heritage or economic activity (Jacinto et al., 2015). It does not conventionally take into account magnitude or severity. Most flood simulation models and administrative decisions rely on hydrological models and a hydrological definition of floodplain, i.e. an area inundated by floods within a particular return period. Therefore, the identification and consequently the mapping of flood prone areas depend on historical records of inundation and discharge, and empirical models of runoff and flood storage.

Floodplain mapping can address a wide-range of physical (e.g. morphological, hydrological), biological, ecological, economic and social problems (Kourgialas and Karatzas, 2011; Lastra et al., 2008; Rohde et al., 2006). The most common way to map a flood is through hydrological modelling. These models characterise terrain through a series of riverbed cross-sections and calculate aspects such as water depth and flow velocity. The models can be either two or three dimensional. Both are used for modelling areas of complex topography such as wider floodplains or broad estuaries but require high quality data and long computation time. Three dimension models consider time as a component (Jha et al., 2012). Hydrological modelling requires several variables, such as maximum monthly and annual discharges, flood-related data, riverbed cross-sections and channel geometry, to calculate runoff and flood storage, stage and duration, flood wave velocity, sedimentation and degradation patterns in the channel and a full documentation of hydrological characteristics, including historical records of inundation and peak discharges (Marriott and Alexander, 1999; Lastra et al., 2008).

Since hydrological models are built using historical, climatic, hydrological and geomorphological variables, they are particularly accurate depictions of flooding reality. They do, however, require large quantities of data and can, as a result, be time-consuming, complex and "skilled" methods. One major issues regarding the use of such models is that it can be impossible to obtain quality and reliable data for all points in a river basin, and some input/calibration data are often affected by non-negligible errors (Baldassarre et al., 2010; Brito et al, 2015). This issue is particularly acute in developing countries where governments cannot afford comprehensive data collection and may not have full access to the expert knowledge required to obtain appropriate outputs (Jha et al. 2012).

The 100 year return period flood is the most widely used method to determine flooding risk within hydrological models (Marriott and Alexander, 1999; Sá and Vicêncio, 2011). However, this is no longer considered accurate, since the increased frequency of floods in the ultimate decades has led to a reduction in their return periods. The return period, namely flood peak effect, is a function of the natural character of the watershed, depending on their climatic setting, its geomorphology, soil and land cover (Deasy et al., 2014; Junk et al., 1989; Zaharia et al., 2015), and is a consequence of the catchment size and discharge variability of the floodplains (Leal and Ramos, 2013; Meraj et al., 2015;

Simonovic and Li, 2003). Therefore changes in the natural character of the watershed, namely soil sealing, modifies the frequency of the return periods and consequently, increases the difficulty in defining and mapping a floodplain. Furthermore, some streams are particularly difficult to model and any hydraulic definition of the floodplain becomes problematic, if (i) the flow is ephemeral and the parent channel may be defined poorly and may change with each discharge event, and (ii) if they have narrow valley bottoms, in which case they might not have floodplains although they may overtop their banks and cause considerable damage (Marriott and Alexander, 1999). Also another weakness mentioned by Marriott and Alexander (1999), is that there is no well-defined threshold between an upland stream that has a floodplain and one that has not.

To address the aforementioned weaknesses in hydrological modelling, morphological analysis can be used to complement hydrological models. This improves flood hazards identification, since these analysis are based on physical criteria that reflect the evidence of fluvial activity (Kourgialas and Karatzas, 2011; Lastra et al., 2008; Santos, 2009). Based on this criteria, landforms/ecosystems are characterised by different land surface parameters, relative to surface water flow and accumulation, microclimate, soil erosion and accumulation, and vegetation (Magalhães, 2001). Therefore, land morphology influences and shapes the distribution of biodiversity, agricultural production and economic activity, and, in turn, its use and management directly influences flood genesis. In this paper, landform mapping through the Land Morphology Concept (LMC) and Land Morphology Mapping (LMM) method is used as a means to complement hydrological modelling and to identify flood risk. LMC is used to define the landscape form arising from its dominant physical structures, linking together the topological and hydrological features (Magalhães, 2001). The LMM method is, in turn, a helpful evaluation tool for modelling natural systems across regions and countries (simply by modifying slope gradient). It identifies and maps, with sufficient detail, wet (concave) and dry (convex) systems through criteria that distinguish slopes, hydrological features and surface curvature.

In this paper, floodplains are considered to be a part of a larger system called a wet system. The wet system is characterised by surface water accumulation, soil fertility due to nutrient retention, riparian and wetland vegetation, and cool air accumulation at night (Geiger, 1965; Magalhães, 2001). It is typically composed of: (1) permanent and temporary streams, and water bodies (2) inland wetland and coastal wetlands (INAG, 2010; IGP, 2010); and (3) valley bottoms which encompass floodplains. Within the LMC, "floodplains" are defined as flat areas located adjacent to a stream in a valley bottom subject to periodic flooding. Valley bottoms, meanwhile, are defined as flat or concave areas adjacent to streams with a slope < 5 %, defined as such because above this value water infiltration retention begins to decrease and runoff increases (Magalhães, 2001; Wysocki et al., 2011). The term "valley bottom" encompasses both the upstream and downstream components of the watershed. The upstream areas are characterised by a higher soil moisture coming from runoff water. These areas even without the risk of flooding, play an important role in land-use planning because they are ecological corridors through which water and air flow, where the storage and distribution of freshwater and accumulation of nutrients is greater. If these areas are impermeabilised or straightened and vegetation removed from channel banks, it can increase surface runoff and streamflow velocities, and transport more sediment. Eroded sediments are major pollutants of surface waters and can further constrict a channel and increase flooding (Konrad, 2015). Also, less water storage capacity and more rapid runoff leads to higher peak discharge rates. Therefore, these areas have high potential of surface runoff susceptible to flash-flood occurrence (Zaharia et al., 2015). In these ecological areas, it is important to differentiate WS from hillslopes and hilltops, once they should receive different uses.

The dry system commonly found on the upper parts of the hillslope profile, where soil erosion and subsurface and surface water movement are dominant processes (Huggett, 2011). It includes (1) Hilltops: that due to erosion processes, encompass the ridgeline in the narrower forms whilst the wider correspond to large hilltops as convex areas with slope < 5 %; and (2) Hillslope or hillside: these landforms are vulnerable to soil erosion, especially those where the slope is > 25 %, still due to the "thermal belt" (drainage winds that carry colder air downslope to the valley bottom) they turn out to be the most ecologically suitable areas for urban development (Magalhães, 2001; Magalhães et al., 2011).

By mapping landforms and specifically distinguishing valley bottoms and hilltops from flat areas, an atypical practice in landform classification, the LMC/ LMM method can delimit floodplains and flood risk areas, where there is currently no or poorly available hydrological data. Also, by mapping and distinguishing hilltops, hillslopes and steep hillslopes, one can more accurately state suitable land uses, which will in turn decrease soil erosion and, consequently, soil loss. Mapping the entire wet system helps to identify areas from upstream to downstream in the watershed, with a high ecological and hydrological sensitivity/value that play a critical role in water balance, specifically in flood risk management. (Junk et al., 1989; Meyer et al., 2009). In their natural condition, these areas provide a variety of provisioning, regulatory and supportive functions (Table 5.1), including flood control, surface water storage and recharge, and simultaneously, at a large scale, they are a fundamental core area and ecological corridor/linkage in Green Infrastructure (Capiella et al., 2007; Opperman, 2014; Wickham et al., 2010). Therefore, mapping landforms through a morphological approach can be easily used as a framework for land-use planning that coupled with flood risk mapping will contribute to limit the consequences of flooding.

Table 5.1. Relation between wet system characteristics, ecological functions and ecosystem services.

Wet system from land morphology	Physical			Biological	Cultural
	Water	**Microclimate**	**Soil**	**Vegetation/habitat**	**Recreational**
Ecological functions	Water accumulation Biogeochemical cycling Flood control Surface water storage and recharge	Temperature regulation Cold air accumulation and air drainage Local breezes (mountain/valley breezes)	Soils/sediments and nutrients accumulation (reducing erosion)	Wet associations Riparian vegetation Wildlife habitat Biodiversity	No building suitability
Ecosystem services	Drinking water and irrigation; water quality; Storing freshwater [provisioning services] Water damage mitigation [regulatory services]	Maintaining microclimatic balance; filtering and diluting pollution, nutrients and sediments sequestration [regulatory services]	Soils/sediments stabilization (river banks) [regulatory services]	Habitat for plants and animals, breeding and feeding areas, productive fisheries [provisioning services]	Recreation, spiritual, aesthetic - provision of water and open space related to parks, greenways, and recreation areas [cultural services]

5.3 | Case study

Since 1884 the Portuguese Public Hydric Domain (DPH) and updated in the DL nº 468/71, water resources have been legally protected. Portugal adopted the EU Water Framework Directive (EC, 2000) and Floods Directive (EC, 2007) into its legal framework, including Law nº. 54/2005 (Water resources ownership), Law nº. 58/2005 (Water Law), Decree-law nº. 115/2010 (Flood Risk). Also the National Ecological Reserve (Decree-law nº. 239/2012) regime gives further attention to flood risk measures and committed all municipalities to map flood risk areas at 1/25 000 scale by 2012. Despite the current legislation on water resources and regulation, not all floodplains in Portugal are mapped and protected. Also, there is some inefficiency between the government and the central administrations from a preventive and risk management perspective (Rocha, 1998; Côrrea, 2013).

Under the Portuguese water framework there are two flood-based definitions, that according to Ramos (2013) resulted from two situations, (1) an overflow of a stream relative to its ordinary bed usually caused by intense rainfall or local runoff (flooding), and (2) a submersion of an emerged area (inundation) caused by floods or dam failure. Since "all floods cause inundations, but not all inundations are due to floods" (Ramos, 2003), some resulting from: i) rise of groundwater table in areas topographically depressed, ii) coastal inundations due to storm surge and tsunamis, iii) overload of the urban storm water management (urban runoff), iv) dam and levee failure, v) ground failures related to erosion, i.e., subsidence and liquefaction of soil. Due to its genesis, inundations can be divided into several types: i) riverine inundation or floods, ii) topographic depressions inundation, iii) coastal inundation and iv) urban inundation.

In Portugal, based on the previous definitions, there is a considerable number of terms used by the mapping community to mean the same thing. For example a floodplain may be referred to (i) “areas threatened by floods”; (ii) “contiguous areas of a stream”; (iii) “inundation areas” and (iv) “flooded areas”. The first two, rely on the concept of a 100 year return period flood. The third and fourth term are defined, according to the hydrological concept of the floodplain mentioned before, as areas that can be inundated by floods or that are inundated depending on a particular return period, respectively. The main problem, however, is that this leads to a certain level of inefficiency in mapping and management application. This efficiency can be addressed via LMC/LMM.

Furthermore, data reliability from the Portuguese hydro-meteorological network has been declining and field data collection in Portugal is nowadays quite sparse (Brito et al., 2015). In fact, flood risk data inputted into hydrological models for the main river basins from the Portuguese Environmental Agency correspond to only to 1 % of the total Portuguese mainland area (APA, 2015). In this paper, the land morphology approach is proposed as a consistent method that might be used as an extra layer of information to map flood risk areas where there is no available data to calibrate the hydrological models. In order to facilitate the identification and management of the landforms, including the wet system, in a way which facilitates flood risk mapping, the land morphology map is applied and analysed at the national level and local level, at an urbanized river basin.

5.3.1 Mainland Portugal

Mainland Portugal, has an area of 92.212 km² and 10.6 million inhabitants (INE, 2012). Due to climatic characteristics (Mediterranean climate), population and activities intensification in coastal areas, especially near floodplains, the country reflects what is happening in EU in terms of floods. During the 1900-2008 period in mainland Portugal, 82 % of the hydro-geomorphological events were floods and 75.6 % of total flood cases were from November to February (Jacinto et al., 2015; Zêzere et al., 2014). Comparatively to precipitation variability, Portugal presents with some frequency very wet and dry years with affecting the hydrological cycle and by consequence the river flow and water resources (Brito et al., 2105). The annual average rainfall varies from over 3 000 mm in the northern mountains to less than 600 mm in southern plains of Alentejo.

The Tagus River divides Portugal’s mainland into two clearly identifiable landscapes (1) enclosed valleys bottoms with abrupt and extensive hillslopes that dominate in the North, e.g. mountainous reliefs in Minho region, Douro valley, Serra da Estrela; and (2) the gently waved relief landscape in south of the River Tagus, that shows peneplain characteristics with gently rolling hills and extensively depressed river basins, e.g. Alentejo peneplain. This is reflected and presented in the land morphology map (Figure 5.1a), which shows that 1.7 % of the total area corresponds to streams and water bodies, including wetlands, 11.2 % are valley bottoms, 20.6 % includes hilltops (ridges and large hilltops), 51.2 % corresponds to hillslopes and 15.3 % to steep hillslopes. The wet system corresponds to approximately 13 % of mainland area.

According to the social consequences of floods, during the same period, from 1900-2008, the Tagus hydrographic region registered 60 % of the total of people made homeless or displaced by flash floods in the Lisbon region (Zêzere et al., 2014). These consequences are also relevant in the Douro, Mondego and Vouga river regions. Despite this evidence and identification of vulnerable areas, approximately two-thirds of the population is living in the coastal floodplains, and the population is still increasing in those areas (INE, 2012), with 50 % of the new urbanized areas located in the 20 km of the coastal (Freire et al., 2009).

5.3.2 Trancão River basin

The Trancão river basin is an intensively urbanised area at the northern limits of Lisbon city (Figure 5.1b). The Trancão River itself is a tributary of the River Tagus that runs for 29 km and its total drainage area is 293 km2 (Trancoso et al., 2009). Despite its location in the North of Lisbon metropolitan area where the urban sprawl increased mainly from the second half of the twentieth century, the urbanisation process in Trancão basin was delayed due to its hard land morphology and an extensive and fertile floodplain, which made infrastructure projects unlikely. However, the proximity to Lisbon city led to the proliferation of the so-called illegal settlements in the 70' and 80's of the twenty century, resulted in an urban continuum between Lisbon and Loures (Leal, 2011). Due to its location and land use changes in the past few decades, from open forests with shrubs and productive agriculture in floodplains to widespread urban areas, Trancão basin reveals severe problems of soil sealing associated with to water quality decrease (SNIRH, 2010). This basin suffer from heavy floods in 1967, 1983 [the peak flood discharge in Ponte Canas hydrometric station in 1983 was 172.36 m^3/s (Leal and Ramos, 2013)], 1997, 2008 [estimated peak flood discharge for 18/02/2008 was 51.67 m^3/s (Leal, 2011)].

From a geomorphological point of view, two areas can be distinguished in Trancão basin (Figure 5.1b): (i) The upstream area, in the north and northwest sector located at Mafra municipality, is the headwaters of numerous streams dominated by strongly embedded valley bottoms with steep hillslopes, at a higher altitude (200–400 m), which drain to Trancão River and its tributaries. Due to steep slopes combined with the clayey composition of the superficial substrate, having reduced permeability, is submitted to a rapid runoff and strong soil erosion and transportation of the materials from the slopes (Pereira and Ventura, 2004); (ii) The downstream area, in the south and southeast sector at Loures municipality, corresponds to an alluvial plain located at lower altitude (2–14 m), mainly the Loures floodplain and the Tagus riverbank (Magalhães et al., 2002). This area is characterized by flat slopes in the alluvial plain, also presenting low permeability (Magalhães et al., 2002), due to the shallow position of the water table, leading to strong sediments deposition in the Loures alluvial valley. Therefore, the upstream characteristics, the low permeability of the deposits and the water table position of this floodplain, the flood risk susceptibility of Trancão basin will increases (Pereira and Ventura, 2004).

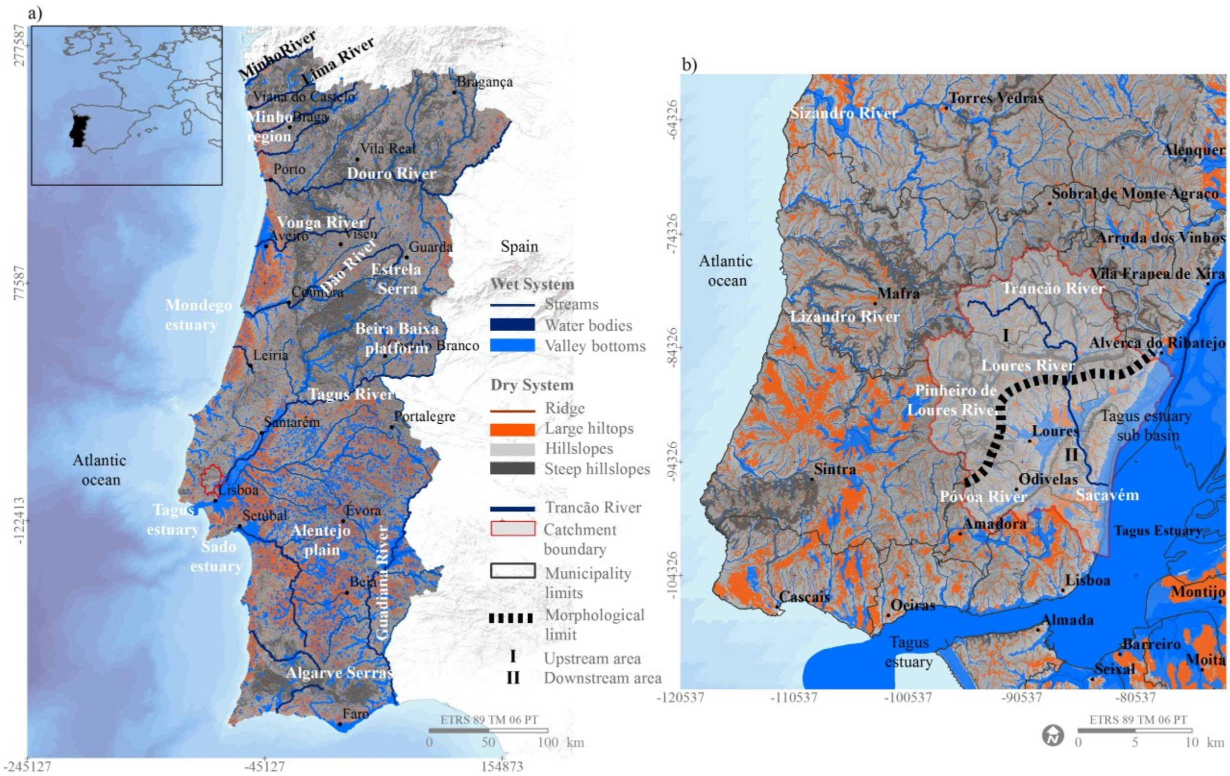

Figure 5.1 Study area localisation with Land Morphology (LM) map for a) Portugal, b) Trancão River basin in the North of Lisbon metropolitan area with two morphological units: I - upstream area and II - downstream area.

5.4 | Data and method

As seen in the data collection section, hydrological data in Portugal quite sparse and there is no single map of floodplains for all the basins. In order to complement existing information, the LMC approach will be used to map Portuguese landforms, namely all river ecosystems in a way which facilitates flood risk mapping at the national level. This is addressed through the application of the land morphology mapping (LMM) method used to identify wet (concave) and dry (convex) systems.

5.4.1 Data

Within this study, the LMM method links topographic and physical characteristics of landscape. The resulting land morphology (LM) map for Portugal is developed in ArcGIS 10.0 ESRI® software and based on the following data (i) 25 m (625 sq m pixel area) spatial resolution digital terrain model (DTM) (INAG, 2010a), (ii) hydrological network and watersheds map at 1:25 000 scale (INAG, 2010b) and (iii) water bodies and wetlands classes from the Portuguese land use/cover map (IGP, 2010).

Also, in order to validate the method the floodplain limits as obtained by hydrological modelling were also used to compare with the landform classes at the national level (Figure 5.1). The available hydrological data mapped for Portugal have diverse backgrounds and do not cover the whole area (Figure 5.2). The following data, available at APA portal (http://sniamb.apambiente.pt/), was used:

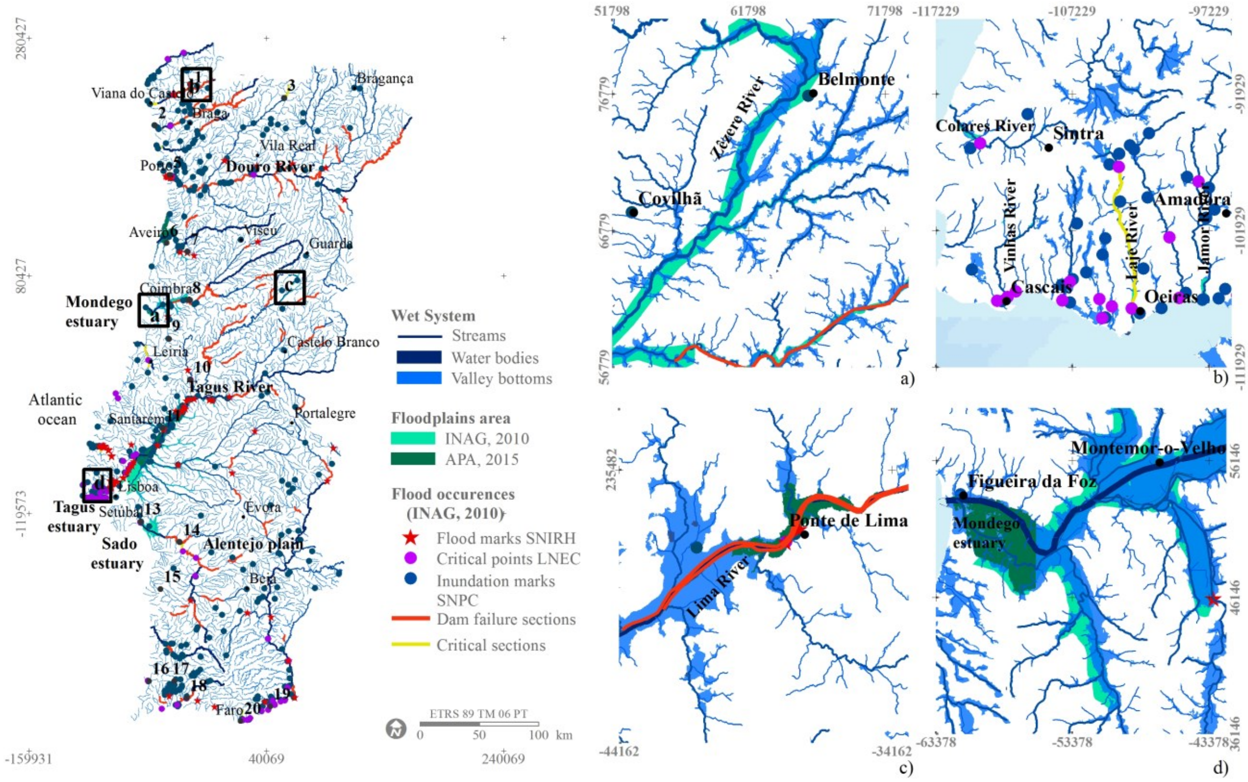

Figure 5.2 Flood risk areas and occurrences in mainland Portugal. Details: a) Zêzere River; b) Colares, Vinhas, Laje and Jamor rivers in the North of Lisbon metropolitan area; c) Ponte de Lima urban area; d) Mondego Estuary.

(1) The Portuguese Water Atlas produced by the former Water Institute (INAG, 2010) provided information on floodplain areas for the 100 year return period flood, for a high number of regional basins, e.g. Douro, Tagus, Mondego, Sado and Vouga, calculated by applying HEC-RAS model, with more detailed studies. It included the "areas threatened by floods" and operative "adjacent areas" for

Tâmega, Zêzere (Figure 5.2a), Colares, Vinhas, Laje and Jamor rivers (Figure 5.2b), mapped from manual digitization of paper studies at scales 1/2 000 and 1/10 000. These floodplains limits from INAG correspond corresponds to 2.18 % of Portugal mainland area.

(2) The Portuguese Environmental Agency (APA, 2015) provided updated information on flood risk areas and floodplains delineation, however this data only refers to 0.97 % of Portugal's area. This was a result of a work developed by the Consortium AQUALOGUS /ACTIONMODULERS based on hydrological and hydraulic modelling for flood calculation with a return period of 20, 100 and 1000 years. These data are only available for some urban areas with potential flood risks (Figure 5.2), namely Ponte de Lima (Figure 5.2c), Ponte da Barca (1), Esposende (2), Chaves (3), Régua (4), Porto (5), Aveiro (6), Águeda (7), Coimbra (8), Mondego Estuary (Figure 2d), Pombal (9), Tomar (10), Santarém (11), Torres Vedras (12), Loures/Odivelas (Figure 1b), Setúbal (13), Alcácer do Sal (14), Santiago do Cacém (15), Aljezur (16), Monchique (17), Silves (18), Tavira (19) and Faro (20) urban areas;

(3) Flood occurrence points from INAG (2010) comprise: (i) flood marks from the National Service on Water Resources Information (SNIRH, 2010); (ii) critical points, including dams failure sections from the Civil Engineering National Laboratory (LNEC, 2009); and (iii) "inundation" marks from the National Civil Protection Association (SNPC, 2009).

Regarding these data, the floodplains area and flood occurrence points are collected and designated as INAG when they were taken from the Portuguese Water Atlas (1) and (iii) and as APA when delineated by the Portuguese Environmental Agency (2). Since APA (2015) and INAG (2010) data do not correspond to the same areas mapped, in this study both information are considered in the comparison in order to ensure a larger area of validation. In Figure 5.2 (details a, b, c, d) several situations are shown: (a) areas with only INAG data, e.g. a demarked area threatened by floods in Zêzere River; (b) areas with well-documented data on flood occurrences points, e.g. the small basins of Colares, Vinhas, Laje, Jamor and Trancão rivers in the North of Lisbon metropolitan area; (c) areas with only APA information, e.g. Ponte Lima urban area in Lima River; (d) areas with two types of data source, APA and INAG floodplain limits, e.g. Mondego Estuary.

5.4.2 Land morphology mapping method

The LMM used to classify landforms is derived from the intersection of the following criteria (1) slope gradient (flat areas), (2) hydrological features and (3) surface curvature:

i) Slope > 5 %, where slopes > 25 % are identified as steep hillslopes.
ii) Slope < 5 % that does not contain streams or ridgelines.
iii) Slope < 5 % that contains either only streams or only ridgelines.
iv) Slope < 5 % that contains both streams and ridgelines in the same polygon.

Areas (i) and (ii) are classified as hillslopes. Areas (iii) are classified as valley bottoms, if they contain streams and are classified as hilltops, if they contain ridgelines. Areas (iv) are complex because they are where the hillslope is absent and where flat areas may be either valley bottoms (concave) or hilltops (convex).

The slope map (1) was used to define flatness or very gently sloping areas in the landscape. It was directly derived from the DTM through the slope function in the Spatial Analyst of ArcGIS 10.0 ESRI®. It was reclassified into two classes: < 5 % and > 5%, corresponding to flat and non-flat areas, respectively. The upper slope limit of flat areas that best represents the landscape in mainland Portugal is 5 %. This is because above this value water infiltration retention begins to decrease and runoff increases (Magalhães, 2001; Wysocki et al., 2011). Below this value, and the resulting map does not have sufficient detail, nor does it identify all floodplains. This limit was confirmed by comparisons with satellite images available at ESRI Base Maps® and land morphology maps drawn at the local scale (Cunha, 2008; Magalhães et al., 2002; Magalhães et al., 2005; Magalhães et al., 2012) showing in detail the floodplains limit.

Regarding the hydrological features (2), Portugal's stream network is derived from INAG hydrological map (2012b) and land use and cover map from IGP (2010). The streams were ranked into four levels according to their watershed size and stream length by Silva et al. (2013), and the ridgelines were generated from the watershed boundaries from watershed map (INAG, 2010b).

The surface curvature (3) or concave-convex boundary, was calculated through the cost allocation function from Spatial Analyst of ArcGIS 10.0 ESRI®. This function identifies and aggregates an area and a cost surface, which are related to the least effort required to travel a distance between streams and ridgelines and the cost of moving up or down in slopes < 5 %. This allows the user to identify a point of inflection where the concavity changes, resulting in valley bottoms and hilltops landforms.

Considering valley bottoms description from the wet system, already defined in section 5.2, the floodplains in the downstream areas of the watershed and all upland river ecosystem, for all the Portuguese river basins will be mapped. Therefore, this mapping limits are evaluated if valley bottoms are coincident with floodplain limits in downstream areas of the watersheds obtained by hydrological definition and modelling. A more detailed study will be carried out with analyses of flood risk occurrence points from INAG (2010). Their location was verified with satellite images available at

ESRI Base Maps® for all cases (see supplementary material), according to distance (proximity) from water bodies and valley bottoms from the LM method. Also for the Trancão river basin, the LM map is studied in detail (Figure 5.1b) as a contribution to validate this morphological approach at a local scale and compared it with the land use/cover map (IGP, 2010) in order to understand the effects of the land morphology and land use in flood risks.

5.5 | Results

The LM approach consistently mapped a GIS land morphology map, at 25 m spatial resolution, for mainland Portugal, which is significant as such a map did not exist previously. This map is able to identify landforms by accurately depicting the wet and dry systems. Consequently, one is able to identify all river ecosystems at the national level.

According to the LM map for Portugal (Figure 5.1), the wet system corresponds to 13 % of the total area. It breaks down into 1.7 % of streams and water bodies, including wetlands, and 11.2 % of valley bottoms including floodplains. This contrast with the 2.18 % (INAG, 2010) and 0.97 % (APA, 2015) flood risk areas based on hydrological data available.

5.5.1 Flood risk areas

The comparison between LM classes and floodplains (Table 5.2) indicates that 80 % of the INAG areas match the WS, namely 14.8 % of the floodplain area is located in water bodies and 65.3 % in the valley bottoms. Moreover, 96.6 % of the APA floodplains correspond to the mapped wet system with 84 % of the area located in the valley bottoms and 12.5 % in the water bodies. In both analyses, the intersections generally occur in downstream areas of the watersheds, where valley bottoms are wider and directly influenced by groundwater level and consequently have a higher flood risk.

Table 5.2 Comparison between landform classes from LM method and floodplain areas mapped by INAG (2.18 % of Portugal area) and APA (0.97 % of Portugal area)

Landform Classes	LM in Portugal total area (%)	Floodplain areas in LM classes (%)	
		INAG	APA
Water bodies	1.7	14.8	12.6
Valley bottoms	11.2	65.3	84.0
Hilltops	20.6	5.5	0.7
Hillslopes	51.2	13.7	2.5
Steep hillslopes	15.3	0.7	0.2

These outcomes demonstrate that not all the WS area is susceptible to flooding since the upstream area of the watershed does not correspond to floodplains. However, these upstream areas as already mentioned in section 5.2, have high potential of surface runoff susceptible to flash-flood occurrence (Zaharia et al., 2015). And if these areas are impermeabilised and vegetation removed, they have less water storage capacity and more rapid runoff leading to higher peak discharge rates. On the other hand, in downstream areas the valley bottoms limits mapped through the landform approach are coincident with floodplain modelled by the hydrological methods. These areas are considered flood risk areas. Therefore the LM approach is a consistent method and might be used as an extra information to map flood risk areas where there is no available data to calibrate the hydrological models.

The majors differences and mistakes from the comparison with the INAG data, with only 80 % of match, might be due to the INAG data source, since some limits result from empirical data with few records and others from the digitisation of the paper-based studies at scales 1/2 000 and 1/10 000. These results are detailed for two situations, Constância and Abrantes urban area in the Tagus River basin (Figure 5.3) and Mondego estuary (Figure 5.4), where there is simultaneously both available INAG and APA data.

From the overlapping information between INAG and APA floodplains areas (Table 5.3), it can be concluded:

Table 5.3 Comparison between floodplain areas mapped by INAG and APA in landform classes (LM).

LM classes and APA floodplain area	Floodplain areas in LM classes (%)		LM classes and INAG floodplain area
	INAG	APA	
Water bodies and APA	2.60	5.85	Water bodies and INAG
Valley bottoms and APA	28.03	62.98	Valley bottoms and INAG
Hilltops and APA	0.16	0.35	Hilltops and INAG
Hillslopes and APA	0.39	0.87	Hillslopes and INAG
Steep hillslopes and APA	0.01	0.03	Steep hillslopes and INAG
LM classes without APA area	68.81	29.93	LM classes without INAG area

i) Although 80 % of the INAG floodplains fit the WS, only 30 % intersect APA floodplain areas. The INAG areas may not have been well mapped since floodplain delimitation is discordant and frequently does not follow the parent stream, as it can be seen in Figure 5.3 at Constância and Abrantes urban area in the Tagus River basin, where INAG areas might have been predicted from empirical data with few records.

ii) 96.6 % of the APA floodplains are coincident with WS and only 68.82 % fit simultaneously INAG floodplain area. These results show that the correspondence between these two datasets is not great, and this 2015 data is better mapped and can improved flood risk mapping (Figure 5.4 at Mondego estuary). However it only exist for few basins and its modelling requires several variables, sometimes difficult to achieve.

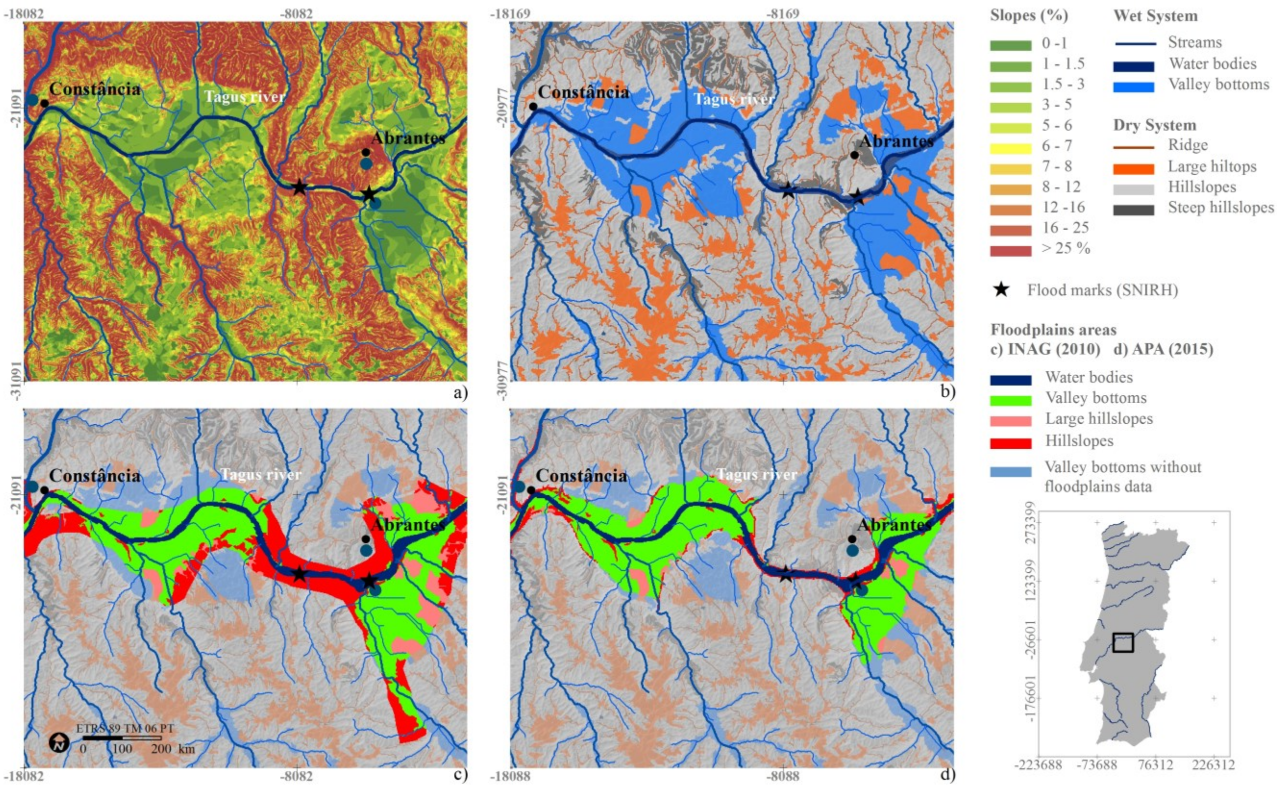

Figure 5.3 Constância and Abrantes urban areas in Tagus River: a) slopes map, b) LM map, c) comparison between landform classes and INAG floodplains; d) comparison between landform classes and APA floodplains.

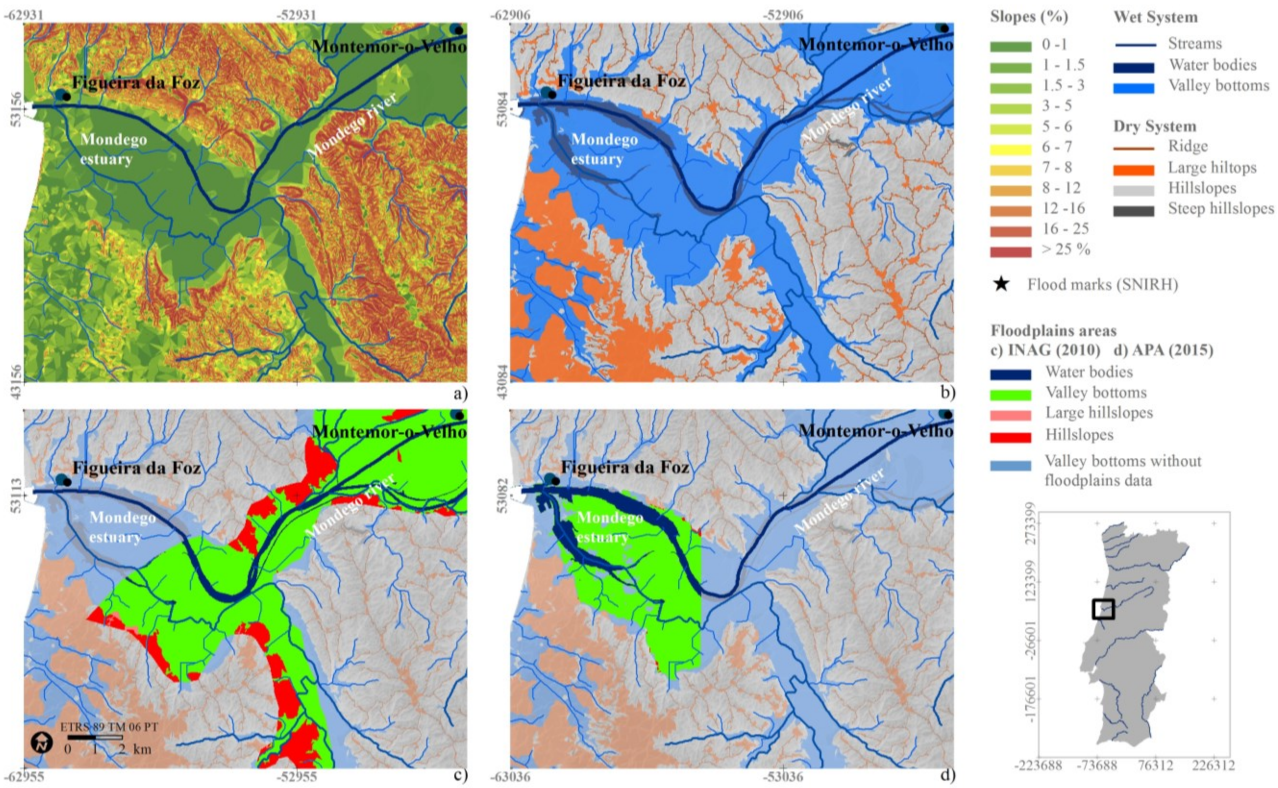

Figure 5.4 Mondego estuary: a) slopes map, b) LM map, c) comparison between landform classes and INAG floodplains; d) comparison between landform classes and APA floodplains.

5.5.2 Flood risk occurrence points

The comparison between the three types of flood risks occurrences, (a) flood marks (SNIRH, 2010), (b) critical points (LNEC, 2009) and (c) "inundation" marks (SNPC, 2009), and the landform classes for Portugal show (Figure 5.5):

i) Flood marks (Figure 5.5a) and critical points (Figure 5.5b) occurred in similar landform classes. They are mainly located in the WS, comprising 64 % (12 % in water bodies and 54 % in valley bottoms) and 80 % (16 % in water bodies to 64 % in valley bottoms) of the points, respectively;

ii) On the other hand, the "inundation" marks (Figure 5.5c) occur in some frequently in hillslopes (54 %). This result shows that these occurrences do not have necessarily to happen in WS areas, since by definition "inundation areas" are the submersion of an emerged area. This situation can be caused by floods but also be due to the failure of dams or other built infrastructures.

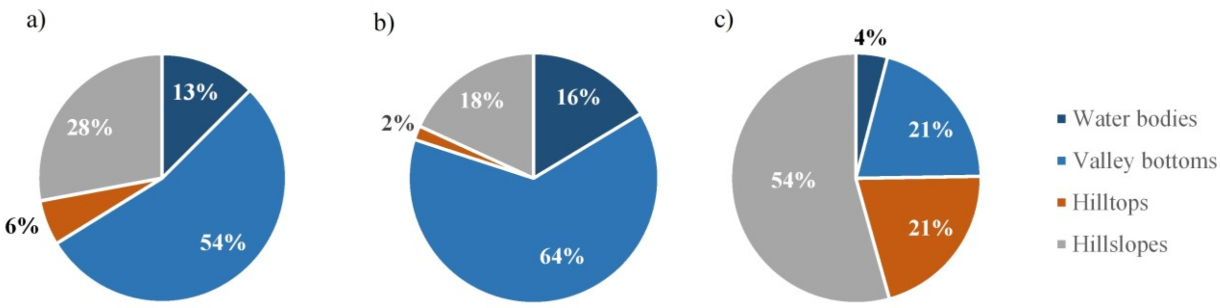

Figure 5.5 Comparison between flood risk occurrence points and landform classes: a) Flood marks (SNIRH), b) Critical points (LNEC), c) Inundation marks (SNPC).

Focusing on the flood marks from SNIRH (Figure 5.5a) with 137 flood risk occurrence points in total Portugal area that are used to calibrate the hydrological models, it can be concluded (Table 5.4) that WS match to 90 points (66 %) of these flood occurrences, 12.4 % are located in water bodies and 53.3 % in valley bottoms. Consequently, the main goal of this comparison is to understand why the remaining 47 points (44 %) do not match the SW areas. A detailed analysis of all the occurrence points, presented in the Supplementary Material, shows that from the remaining 47 points, 20 are coincident with the APA floodplain area and two with INAG, that will be further detailed. In most situations, the remaining points are located in a shorter distance from the WS boundary (less than a pixel), this difference is a consequence of the model spatial resolution (25 meters pixel). As a physical method, LMM has limitations due to the data input, depending on the mapping resolution of DTM and the hydrological network. A higher DTM resolution improves the quality of the slope map and finer topographic details of the landscape.

It was also demonstrated (Table 5.4) that, from the 137 flood risk occurrence, 74 points match APA area, and 44 points are located inside INAG limits, even though APA comprises less area than INAG, only 0.97 % of Portugal total area against of the 2.18 % area from INAG. As it expected APA limits have a higher correspondence with flood risk occurrence since these flood risk occurrences were used in the hydrological modelling process.

Table 5.4 Detailed analysis of the 137 flood marks (INAG, 2010)

<table>
<tr><th>Class</th><th>Description</th><th colspan="2">Flood marks</th><th colspan="3">Significance (%)</th></tr>
<tr><td>1</td><td>Water bodies</td><td>1</td><td rowspan="8">90</td><td>0.7</td><td rowspan="4">12.4</td><td rowspan="8">66</td></tr>
<tr><td>101</td><td>Water bodies and floodplains INAG</td><td>2</td><td>1.5</td></tr>
<tr><td>1001</td><td>Water bodies and floodplains APA</td><td>3</td><td>2.2</td></tr>
<tr><td>1101</td><td>Water bodies and floodplains INAG/APA</td><td>11</td><td>8.0</td></tr>
<tr><td>10</td><td>Valley bottoms</td><td>20</td><td>14.6</td><td rowspan="4">53.3</td></tr>
<tr><td>110</td><td>Valley bottoms and floodplains INAG</td><td>13</td><td>9.5</td></tr>
<tr><td>1010</td><td>Valley bottoms and floodplains APA</td><td>24</td><td>17.5</td></tr>
<tr><td>1110</td><td>Valley bottoms and floodplains INAG/APA</td><td>16</td><td>11.7</td></tr>
<tr><td>90</td><td>Steep hillslope</td><td>7</td><td rowspan="6">47</td><td>5.1</td><td>5.1</td><td rowspan="2">19</td></tr>
<tr><td>0</td><td>Hillslope</td><td>19</td><td>13.9</td><td rowspan="4">23.4</td></tr>
<tr><td>100</td><td>Hillslope and floodplains INAG</td><td>1</td><td>0.7</td><td rowspan="4">15</td></tr>
<tr><td>1100</td><td>Hillslope and floodplains INAG/APA</td><td>1</td><td>0.7</td></tr>
<tr><td>1000</td><td>Hillslope and floodplains APA</td><td>11</td><td>8.0</td></tr>
<tr><td>1030</td><td>Large hilltops and floodplains APA</td><td>8</td><td>5.8</td><td>5.8</td></tr>
<tr><td>-</td><td>Total</td><td>137</td><td></td><td>100</td><td>100</td><td>100</td></tr>
</table>

Class is the corresponding code to Description, according to point's location into landform classes and floodplains area.

Analysing in detail these 74 points inside APA limits, 54 occurrences matches WS and the remaining 20 points are located in:

i) Hillslopes (eleven points), with only three occurrences that need attention due to the distance from WS (> one-pixel size resolution), corresponding to point ID 28 at Ponte da Barca (Figure 5.6a), and points ID 37 and ID 38 at Trancão river basin (Figure 5.6b);

ii) Large hilltops (eight points), points ID 40 to ID 45 at Torres Vedras urban area (Figure 5.7a) and points ID 46 and ID 47 at Sizandro river (Figure 5.7b);

iii) Hillslope (one point) that is simultaneously in INAG and APA floodplain areas - Point ID 39 at Unhos urban area in Trancão river basin (Figure 5.8b) distant 17 m from valley bottom limit (less than a pixel with 25 m resolution).

Consequently, these points location can be used in the future work to accurate WS mapping.

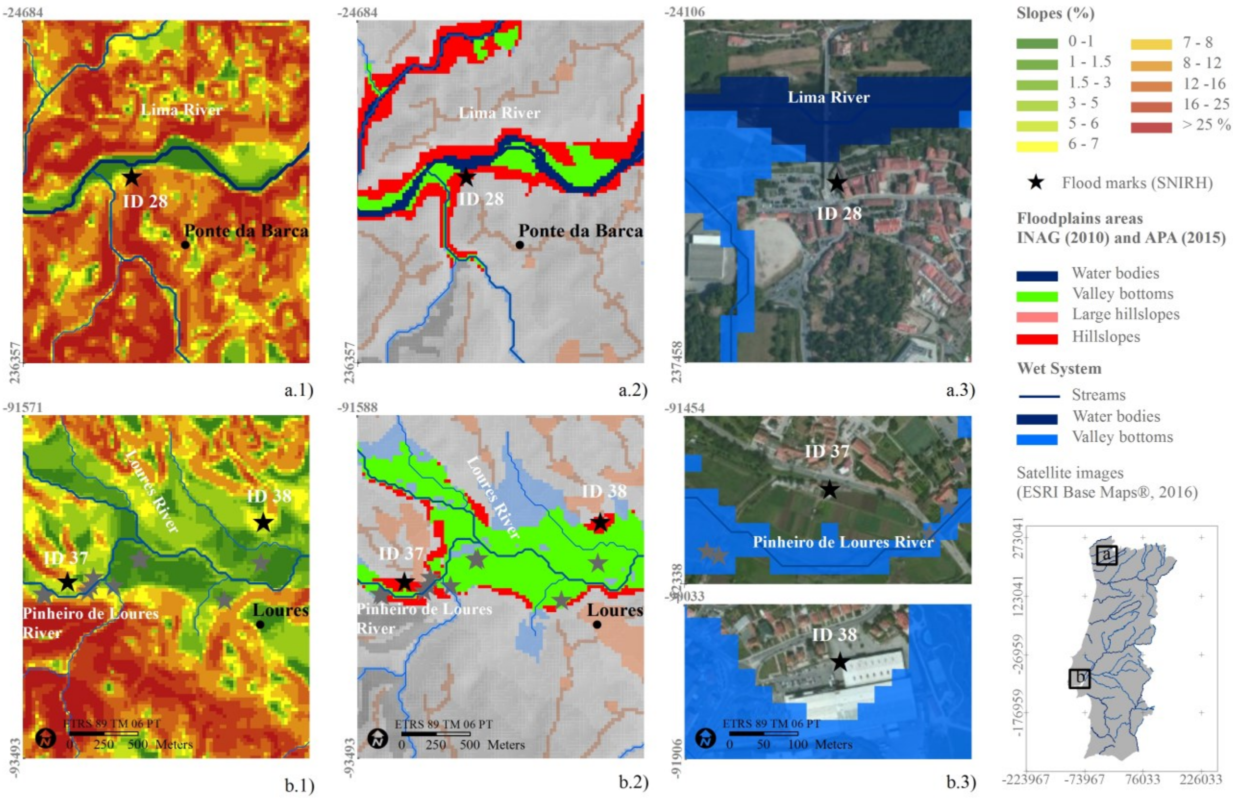

Figure 5.6 a) Point ID 28 – Ponte da Barca in Lima River basin, b) Point ID 37and ID 38 – Loures and Pinheiro de Loures in Trancão River basin

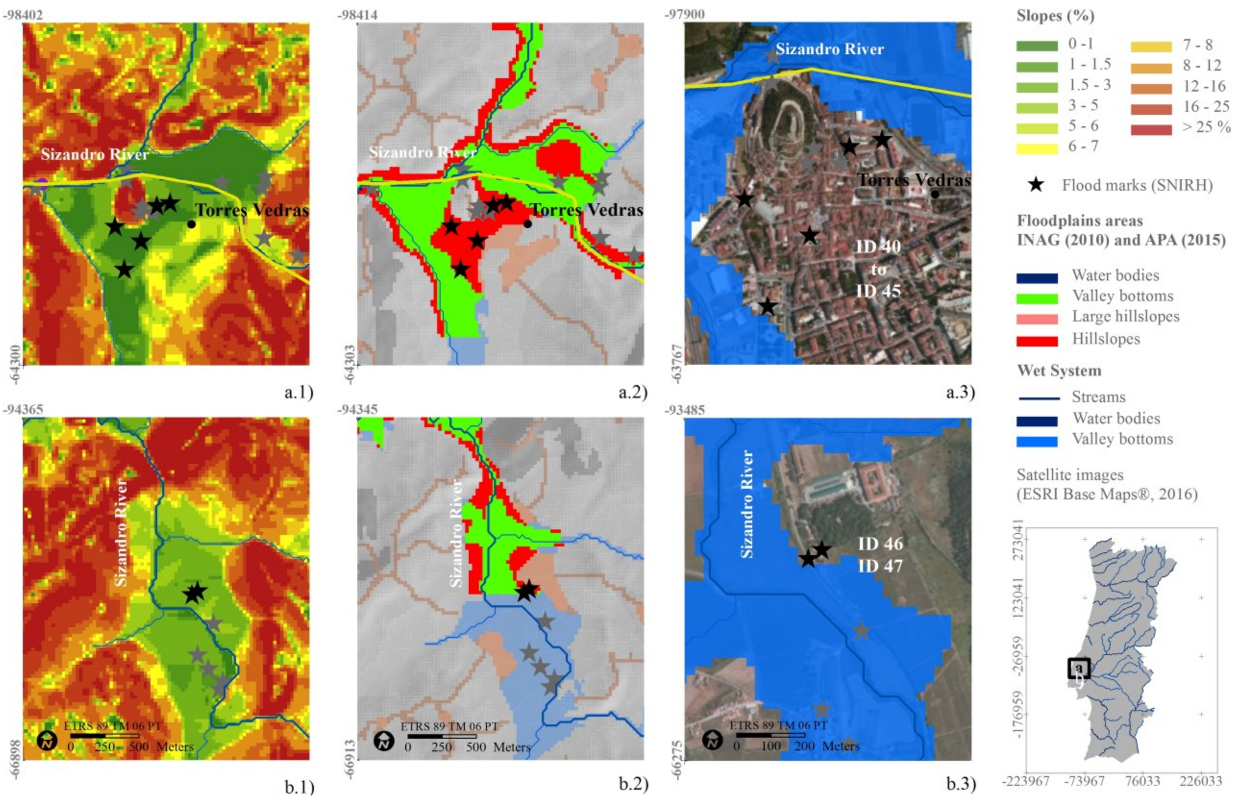

Figure 5.7 Sizandro River basin: a) Point ID 40 to point ID 45 at Torres Vedras urban area; b) Point ID 46 and point ID 47 –Penedo in Sizandro River

As already mentioned from the analysis of all 137 points of flood marks (SNIRH, 2010), 44 points are located inside the INAG area (Figure 5.8 and Supplementary material Table S5.1). From these 44 points, 42 occurrences are coincident with WS and the remaining two points are located in:

i) Hillslope - Point ID27 at Ortiga, in Tagus River (Figure 5.8a), located at 100 m distance from the stream and in an area with 8 % slope;

ii) The occurrence already mentioned for APA analysis, the point ID 39 at Unhos urban area in upstream basin of Trancão River (Figure 5.8b) located simultaneously in hillslope (from LM map) with floodplain areas (from INAG and APA).

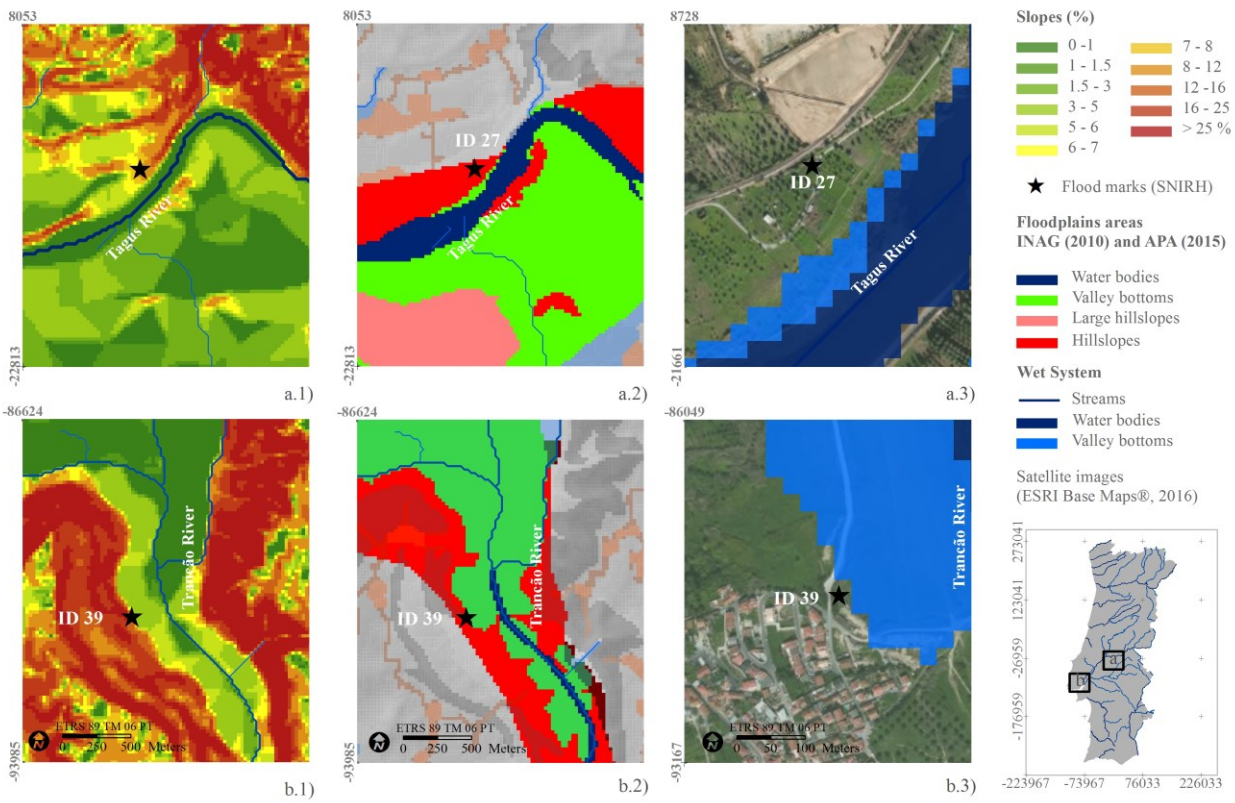

Figure 5.8 Flood occurrences in flood risk areas from INAG 2010: a) Point ID 27 – Ortiga in Tagus River basin; b) Point ID 39 – Unhos in Trancão River basin (upstream basin)

The results demonstrate that of the 47 flood risk occurrence points that do not intersect the WS, 26 of them also do not intersect APA or INAG floodplains areas. The location of all these points were verified for mainland Portugal (Supplementary Material) and some particular examples located in the Madalena urban area (Tâmega River), Sabor River, Guadiana River basin, Coja River, Seda River, Cobres stream (Guadiana River basin) are presented in Figure 5.9. The difference between the points and the WS areas are a consequence of the model spatial resolution (25 meters pixel). Most of these points are located in hillslopes at a distance < 25 meters (less than one pixel) from the valley bottom's limit.

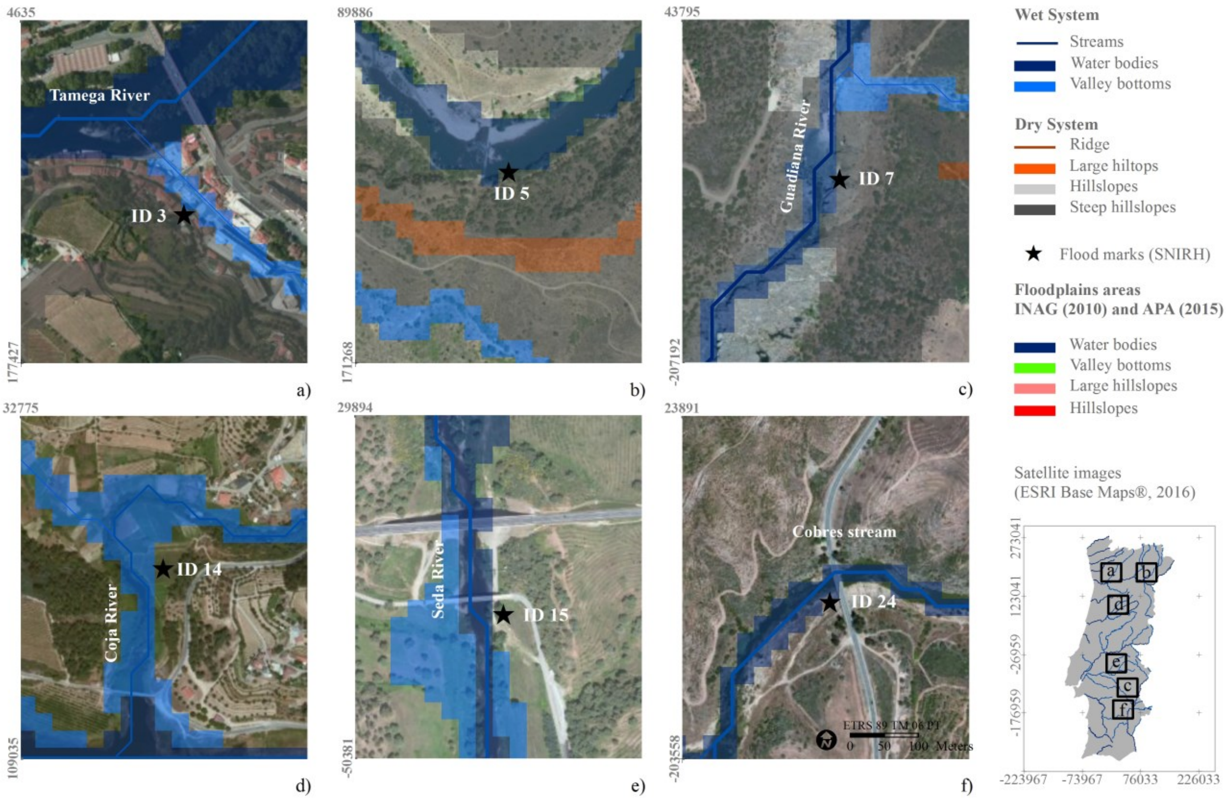

Figure 5.9 a) Point ID 3 at Madalena urban area in Tâmega River (Torrão dam), b) Point ID 5 at Sabor River, c) Point ID 7 at upstream in Guadiana River basin, d) Point ID 14 in Coja River (Dão River tributary), e) Point ID 15 in Seda River, f) Point ID 24 Cobres stream in Guadiana River basin

5.5.3 River basin perspective – Trancão River

According to the morphology of the basin (Figure 5.1b) two areas were distinguished – upstream and downstream areas. Demonstrated in Figure 5.10 a and b, and corresponding to slope and LM map downstream area of Trancão River basin, the following areas have different responses to flooding: (a) the first area in the upstream basin having reduce permeability and steep slopes, have a rapid runoff and strong soil erosion; (b) the second area characterized by flat slopes, low permeability, shallow position of the water table consequently with a strong sediments deposition in the Loures alluvial valley, is more vulnerable to floods, especially at downstream sector of Trancão River by its narrow shape and influence of tides.

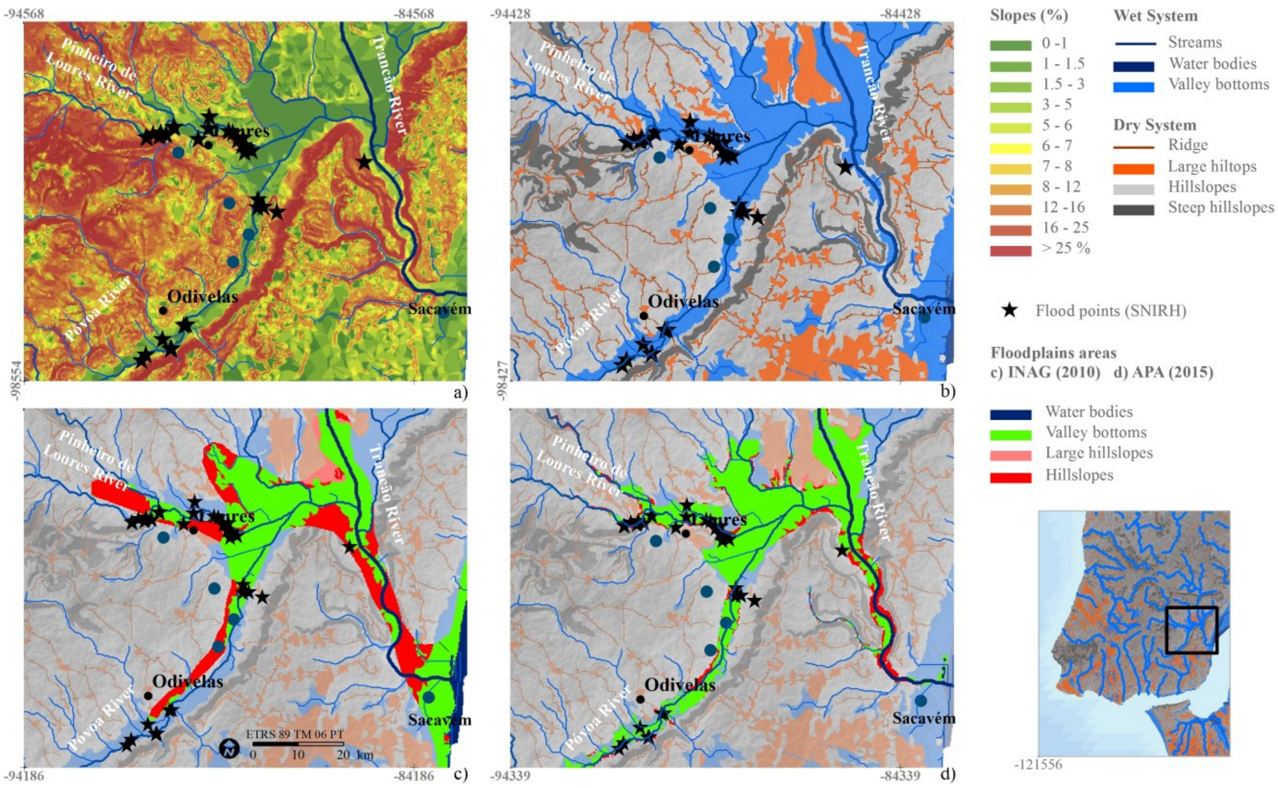

Figure 5.10 Downstream area of Trancão River basin: a) slope map, b) LM map, c) comparison between landform classes and INAG floodplains, d) comparison between landform classes and APA floodplains

The comparison between LM classes and floodplain areas (Figure 5.10c and d, and Table 5.5) indicates that WS comprises 15.4 % (1.5 % water bodies and 13.9 % valley bottoms) of the Trancão basin, together with 8.4 % of the INAG floodplains and 4.2 % of the APA limits.

Table 5.5 Comparison between landform classes from LM method and floodplain areas mapped by INAG (8.4 % of Trancão River basin) and APA (4.2 % of Trancão River basin)

Landform Classes (LM)	LM in Trancão basin (%)	Floodplain areas in LM classes (%)	
		INAG	APA
Water bodies	1.5	17.6	2.3
Valley Bottoms	13.8	62.3	84.2
Hilltops	10.5	4.4	1.2
Hillslopes	64.5	13.5	12.2
Steep hillslopes	9.6	2.2	0.2

In this basin, 80 % of the INAG areas match WS (17.6 % in water bodies and 62.3 % in valley bottoms) and 86.5 % of the APA floodplains corresponds to WS, with 84.2 % located in valley bottoms and 2.3 % in water bodies. Relatively to the INAG data, the comparison between landform classes and INAG floodplains particularly demonstrates the discrepancy between manual and automatically modelled data. In Figure 5.10c, it is evident that in some areas floodplains do not follow the parent stream (Odivelas) and 2.2 % occur in steep hillslopes (> 25 % slope) at higher altitude. From the comparison with the APA (2015), differences are evident in the terminal sector of the Trancão River where valley bottom is enclosed by narrow hillslopes (Figure 5.10d).

From the 137 flood marks (INAG, 2010), 35 are located in the Trancão river basin. From those, 30 flood marks are situated in the WS. The other five occurrences are located in hillslopes and in:

i) INAG and APA floodplain areas – Point ID 39 (Figure 5.8b) located at 17 m from the valley bottom (one pixel of spatial resolution);

ii) APA floodplain – Point ID 37 at Loures urban area and Point ID 38 at Barro urban area (Figure 5.5b), both in areas with 6–7 % slope and at a distance of 87 m and 50 m from the valley bottom, respectively;

iii) Hillslopes – Point ID 21 at Pinheiro de Loures River distant 45 m from the stream, and Point ID 22 at Loures urban area (Frielas bridge) distant 250 m from the valley bottom, which being a built up area decreases the return period of the floods.

5.4 Flood risk and land use

The analysis of the land use/cover map (IGP, 2010) at the national level, with an exemplifying description for the North part of Lisbon metropolitan area (Figure 5.11a), indicate that 85 % of the artificial area is well located on hillslopes (54 %) and hilltops (31 %). However, 5 % of WS total area, including valley bottoms, wetlands and floodplains (Figure 5.11b) is occupied by built infrastructures (artificial areas class of the land use and cover map), where floods occur. This could be crucial in flood risk events since the built areas contribute to the decrease of water infiltration rates and flood return periods, and will increase peak flow as already referred. This urbanisation is evident in Trancão River basin, mainly located in the downstream area as detailed in Figure 5.11c. The artificial area in Trancão River basin corresponds to 28 % of the total area of the basin (99 km^2). This artificial area is located in hillslopes (64 %), hilltops (17%), valley bottoms (17 %) and steep hillslopes (2 %).

In the WS area, corresponding to 15.3 % of the total area of the Trancão River basin (Table 5.5), 4.85 % are artificial areas located in valley bottoms. This means that 34 % of the valley bottom areas are already sealed (17 km^2). The basin land use/cover, which was predominantly agricultural in a very fertile and large floodplain is becoming densely occupied by built infrastructures, particularly in the downstream area; and the open forests with shrubs that cover the steep slopes in upstream area is being progressively replaced by eucalyptus and pine forest often subject to wildfires leaving the soil subject to erosion also improving the downstream flood risk.

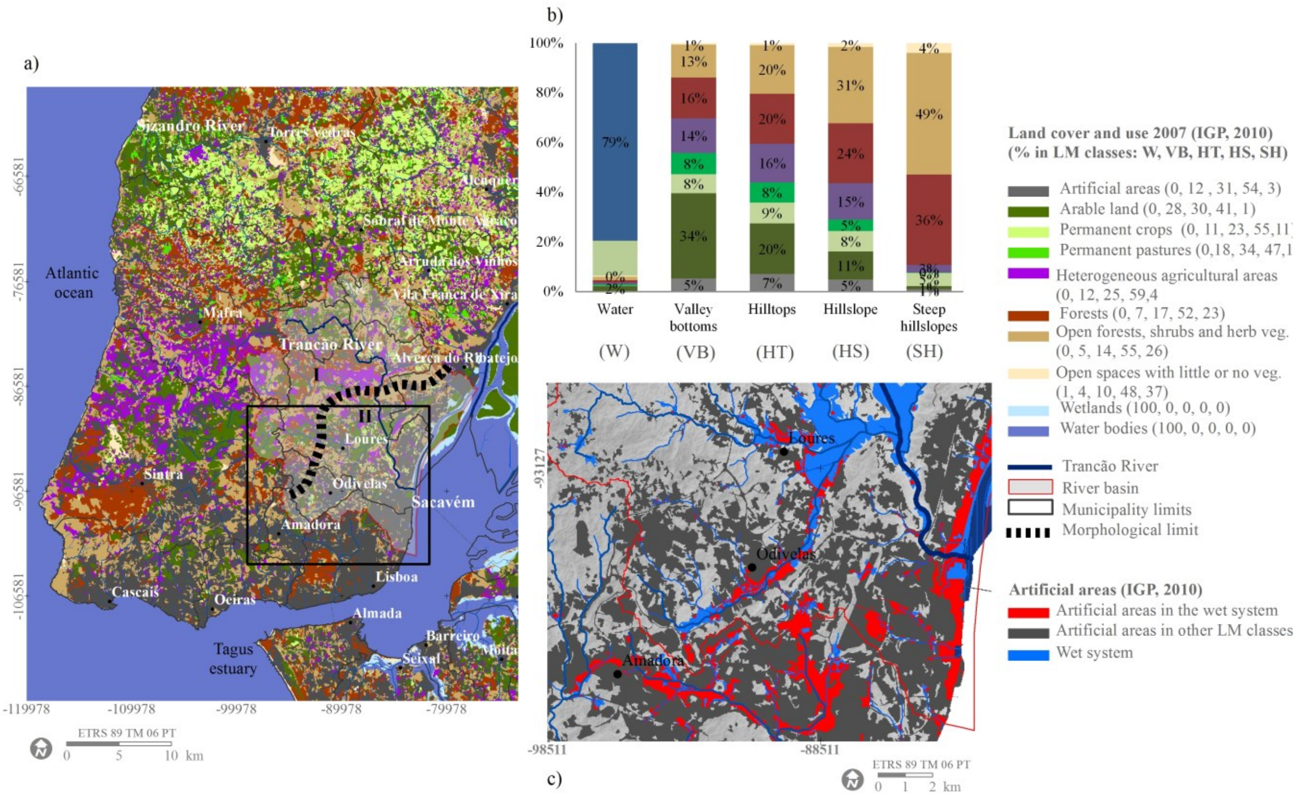

Figure 5.11 a) Detail of Land use/cover map (IGP, 2010) for North of Lisbon metropolitan area; b) Distribution of land use and cover classes (IGP, 2010) according to landform classes; c) Artificial areas in WS detailed for the downstream area of Trancão River basin.

5.6 | Discussion

The LM approach is a helpful evaluation tool for modelling natural systems across from national to local levels, as input criteria to define and map landforms according to their hydrological position in the watershed. The LMC and LMM method is also a valuable complementary tool in a higher-level based planning to assist policymakers and planners in flood risk and land use management. By quantitatively categorising and mapping landforms, including floodplains and flood risk areas, is an essential tool to reduce flooding and associated costs, also by distinguishing valley bottoms and hilltops from flat areas, an atypical practice in landform classification, it can more accurately state suitable land uses. It was shown that LMC/LMM is robust enough to support environmental and planning authorities in taking decisions based on a more thorough analysis of land value and ecological functions.

Additionally, by specifically mapping the entire wet system in order to identify areas from upstream to downstream in the watershed, the LMC/LMM method can delimit floodplains and flood risk areas and, where there is currently no or poorly available hydrological data to calibrate the models. Therefore, the LMC/LMM approach is a complementary option which is less demanding in terms of data required and consequently less time-consuming than hydrological methods, especially where data collection is limited, as is the case in Portugal. In addition to being easily and economically applied to large areas, this morphological method consistently mapped floodplains, as valley bottoms are coincident (96.6 % of APA floodplains limit) with the existent floodplain limit in downstream areas of the watersheds. These floodplains data and maps are the results of the recent study provided by the Portuguese Environmental Agency on updated information on flood risk and vulnerability maps, which should be included in municipal plans under the Decree-law nº. 115/2010 (Flood Risk), and Decree-law nº. 239/2012 (Portuguese Ecological Reserve). Although the land morphology mapping criteria are applicable to the Portuguese situation, they can be applied internationally, just by modifying the slope gradient relative to local conditions.

As a physical method, based on slope gradient (flat areas), hydrological features and surface curvature, the LMM method is a simplification of the reality depending on the mapping resolution of DTM and hydrological network. A higher DTM resolution improves the quality of the slope map and highlights finer topographic details of the landscape given that the density and location of streams and ridgelines permit the identification and representation of the landforms in a more accurate way. If they are absent, valley bottom and hilltop recognition are not possible. In future developments, the LM mapping method should include flood risk occurrences points, so to easily distinguish larger hilltops and valley bottoms in similar situations of slope and elevation.

Since there is a direct relation between incorrect land use practices and flood risk and frequency, the urban context of Trancão river basin in the North of Lisbon metropolitan area (Figures 5.10 and 5.11) contributed to better understand the upstream and downstream characteristics of the basin morphology at a local-scale. Despite not all wet system area is susceptible to flooding, only in downstream areas where the valley bottoms are coincident with floodplain modelled, it was demonstrated that is mandatory to map all the river valleys and not only floodplains, since soil sealing in upstream and downstream areas lead to a different response to flooding.

Furthermore, this work will contribute to the understanding of the morphology, ecology and land use of watersheds and identify the areas in the wet system where to promote natural floodplain restoration, appropriate agricultural practices, and human activities location, in order to reduce runoff and downstream flood risk. This can be accomplished by integrating the LM approach in higher-level based planning instead of a reaction to local decisions on flood hazards, namely into the Green Infrastructure strategy (Liquete et al., 2015). It also may support the Portuguese Ecological Reserve and Ecological Network framework (Magalhães et al., 2013) as a planning tool to increase ecological connectivity, conserving and buffering core areas such as floodplains.

5.7 | Conclusion

The land morphology, the land use, and management directly influence flood risks genesis. However, attention is not always given to the underlying geomorphological and ecological processes that shape river valleys and their floodplains. Thus, within this LM approach, the wet system is a broad concept, which comprehends streams, permanent and temporary, wetlands, and valley bottoms, including floodplains, as flat and concave areas contiguous to streams in which slope is less than 5 %, along all over the drainage network of the watershed. This holistic approach allows mapping landforms namely all river ecosystems including upstream and downstream areas of the watershed. As mapping the entire wet system for Portugal, one can provisionally delimit floodplains and potential flood risk areas, where there is no available hydrological data. Additionally, since not all floodplains in Portugal are mapped and protected, and the building area is still increasing in those areas, the land morphology map can be easily used as a valuable complementary tool for land-use planning that coupled with flood risk mapping will contribute to limit the consequences of flooding.

5.8 | References

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5.9 | Supplementary material

Table S5.1 Detailed analysis of flood risk occurrence points

Code INAG (2010)	Point ID	Class	Geographical Coordinates		Description	Distance (m)from	
			X	Y		Stream / Water bodies	Valley Bottom
5209	1	90	-40 209.745	163 616.011	Estuário do Douro	15	-
5214	2	90	-42 561.758	164 263.591	Estuário do Douro	50	-
5980	3	90	4 820.038	177 673.604	Tamega River - Torrão dam	35	5
6361	4	90	62 126.263	175 064.163	Tua River	10	-
6362	5	90	90 118.997	171 560.216	Sabor River	5	30
6382	6	90	-26 071.231	1 306.795	Nabão River	50	30
6420	7	90	44 033.465	-206 946.477	Guadiana River – upstream Alqueva dam basin	1	5
5208	8	0	-41 789.116	164 368.413	Rio Douro River (right margin)	37	12
5222	9	0	-40 894,762	163 940,102	Rio Douro River	268	143
5201	10	0	-40 290,791	163 632,223	Rio Douro River	31	15
5212	11	0	-40 028,481	163 608,839	Rio Douro River	8	-
6371	12	0	92 760,983	134 462,653	Águeda River	-	-
6378	13	0	-20 762,788	97 440,438	Águeda River - downstream	35	-
6379	14	0	27 660,826	101 912,575	Coja River (Dao river tributary) -upstream Fagilde dam	30	10
6412	15	0	30 027,969	-49 652,651	Seda River - upstream Maranhão dam	5	-
5250	16	0	-97 641,091	-62 942,019	Sizandro River	32	18
5254	17	0	-97 527,070	-63 136.805	SizandroRiver	220	140
5252	18	0	-97 541.323	-63 165.311	Sizandro River	289	187
5241	19	0	-96 586.393	-63 421.859	Sizandro River	91	75
5239	20	0	-96 382.105	-63 497.873	Sizandro River	92	55
5260	21	0	-91 079.995	-92 188.762	Pinheiro de Loures River – Trancão basin	45	-
5282	22	0	-88 143.674	-94 643.225	Póvoa stream - Trancão basin	600	250
6416	23	0	75 571.615	-106 919.950	Guadiana river	-	-
6418	24	0	10 936.036	-207 418.416	Cobres stream - Terges stream basin	5	-
4094	25	0	31 982.879	-259 416.499	Cadavais stream	88	35
6421	26	0	-41 062.047	-271 796.995	Farelo stream – tributary of Odeáxere stream	10	-
5656	27	100	9 546.683	-22 321.274	downstream Belver dam – Tagus River	100	-
4087	28	1000	-23 882.163	237 721.463	Lima River	87	32
5203	29	1000	-44 716.935	164 447.914	Douro River	-	25
5206	30	1000	-43 519.999	164 321.381	Douro River	21	6
5216	31	1000	-43 027.545	163 975.979	Douro River	3	-
5217	32	1000	-43 037.804	163 948.621	Douro River	23	-
5211	33	1000	-40 988.302	163 918.714	Douro River	126	-
5210	34	1000	-41 065.049	163 820.739	Douro River	9	-
5221	35	1000	-40 064.069	163 608.459	Douro River	12	-
5219	36	1000	-40 131.018	163 335.761	Douro River	10	-
5266	37	1000	-89 828.889	-91 777.157	Trancão River	150	87
5258	38	1000	-91 244.412	-92 195.200	Pinheiro de Loures River – Trancão basin	112	51

Table S5.1 Detailed analysis of flood risk occurrence points (cont.)

Code INAG (2010)	Point ID	Class	Geographical Coordinates		Description	Distance (m)from	
			X	Y		Stream / Water bodies	Valley Bottom
5276	39	1100	-85 827.429	-92 925.368	upstream basin - Trancão River	260	17
5247	40	1030	-97 335.723	-63 125.487	Sizandro River – Torres Vedras	197	40
5255	41	1030	-97 415.098	-63 133.424	Sizandro River – Torres Vedras	191	90
5253	42	1030	-97 454.785	-63 196.925	Sizandro River – Torres Vedras	247	150
5248	43	1030	-97 759.057	-63 317.310	Sizandro River – Torres Vedras	299	60
5246	44	1030	-97 454.785	-63 442.988	Sizandro River – Torres Vedras	384	226
5245	45	1030	-97 651.476	-63 595.922	Sizandro River – Torres Vedras	187	27
5237	46	1030	-93 121.378	-65 693.274	Sizandro River - Penedo	106	16
5238	47	1030	-93 082.441	-65 654.338	Sizandro River - Penedo	142	42

6 | CONCLUSIONS

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This research aimed to clarify the role of ecological network (EN) and land morphology (LM) in landscape planning at a national level. Therefore, in this thesis, it is recognised the importance of the EN as an ecologically based tool towards a more sustainable landscape planning, strengthening the notions of connectivity and multi-functionality of landscape. Also, the LM is considered as a helpful evaluation tool to quantitatively categorised and mapped landforms, important to take planning decisions based on a more thorough analysis of the land value and its ecological functions, namely as component of EN delimitation and flood risk mapping.

In the previous chapters, it was addressed: i) the EN concepts, legislative background, key principles and definitions, mainly within the 2015 Green Infrastructure (GI) framework and presented a methodology to map the National Ecological Network (NEN) for mainland Portugal; ii) a detailed study of the land morphology concept (LMC) and a mapping (LMM) method at the national level; and iii) the morphological approach was applied to map wet system (WS) at a national scale, demonstrating its importance as a preliminary tool for floodplains delimitation and flood risk mapping.

The following section presents the overall conclusions for the research objectives, the contribution to science and society and future research. The conclusions concerning the main research questions can be summarised as follows:

Ecological Network (EN)

- The EN is considered a **spatial concept** based and a **planned network** recognised as multi-level ecological evaluation criteria which integrates, in a single framework, the physical and biological systems. This network provides the physical conditions that are necessary for maintaining or restoring ecological functions, supporting biological and landscape biodiversity as well as the sustainable use of natural resources. The physical system includes geology/geomorphology, land morphology, soil, water and climate components, whilst the biological system comprises habitat and vegetation, and the interactions between them.

- This research clarifies the potentiality of the EN, its importance and function within GI approach, by providing a **spatial framework** defining areas of existing and potential ecological connectivity, at various scales and planning levels. The NEN classification indicated which areas are highly valuable ecosystems, e.g. significant soil fertility and productivity, natural vegetation of high conservation, etc. Therefore, the EN establish the theoretical framework of the GI by setting up the primary ecological functions of the GI and underpins the primary notions of connectivity, mobility (accessibility), multifunctionality and scale, as the “essence” of the GI. The GI as broader-scale tool must involve the integration of stakeholders and policies in the landscape management.

- Based on **multi-criteria ecological** approach, the EN design required a **transdisciplinary** effort based on different sciences, highlighting the support of academic researchers and practitioners with different scientific backgrounds namely geomorphology, soil sciences, phytosociology, agronomic engineering, coordinated by a landscape architect, with an integrative methodology;

- Integrating **landscape scale in the design.** The landscape scale analysis is used for identifying, mapping and prioritising ecological essential areas. The EN criteria and maps, based on 25 m spatial resolution DTM, was successfully applied at the national level (NEN), providing a network that can be replicated to other planning levels, regional and municipal level. Those maps represent an effective planning tool and important political instrument for public institutions at regional and municipal levels, namely the Fundamental Network of Nature Conservation (RFCN), comprising the National Ecological Reserve (REN), National Agricultural Reserve (RAN) and Public Hydric Domain (DPH) and the upcoming Portuguese GI.

Mapping EN at the national level

- A **GIS-based integrated mode**l (Esri®Argis10 software) was used to implement the methodology for EN mapping at the national scale. The method is made up of a sequence of analyses and evaluations that are driven by a GIS supported assessment of several indices/models used for each EN component;
- The NEN physical and biological components and the specific mapping methods were **assessed individually**, according to ecological value, specific ecological functions, hydrologic availability, soil genesis processes and fertility, plant biodiversity (species) and habitat resources;
- The NEN components were **integrated and hierarchized** in two levels according to the ecological value or sensitivity, and function of each component. The first level of NEN (NEN1) presented has a higher value than the second (NEN2) and consequently justifies special preservation and recovery measures. NEN1 components – Streams, marine and coastal water, transitional waters (estuaries), inland waters, wetlands, valley bottoms, coastal areas, soils of very high and high ecological value, steep slopes, geosites, natural and semi-natural vegetation of very high and high conservation value, Natura2000; Important Bird Areas; Wetlands - Ramsar Convention; Biosphere and Biosphere Reserve; National network of protected areas; NEN2 components - Pleistocenic fluvial terraces, highlands, maximum infiltration areas, natural and semi-natural vegetation with moderate, low and very low conservation value.

- The NEN1 has the greatest ecological sensitivity due to high biodiversity and ecosystem stability, which equally means they are more vulnerable to anthropogenic activity. NEN1 covers a total of **67 %** of mainland Portugal, yet only **25 %** is legally protected in nature conservation areas. NEN2 correspond to less sensitive areas and represents 55 % of Portugal´s mainland area. Priority must be given to NEN1 areas should receive protection from the Government in order to avoid/decrease landscape fragmentation, environmental risks and natural disaster prevention.

- From the main results, 61 % of NEN1 area results from the individual expression of components in the landscape, safeguarding a restricted although a relevant set of ecological functions. In this perspective, to ensure that the desired ecological functions of the network are accomplished, all the components are equally indispensable to landscape connectivity and it was not possible to justify a hierarchy among them.

Ecological Network vs conservation strategies

- The NEN results illustrated that the criteria used in conservation areas, namely Natura 2000 in previous years are, in fact, insufficient to ensure the ecological balance of landscape, as was determined by 2011 Biodiversity Strategy. Therefore, the NEN indicates the areas that should be protected, in addition to nature conservation areas, showing the importance of protecting these ecosystems. Specifically, the NEN1 that comprehend areas of high biological sensitivity and productivity, with higher importance in nutrient storage and distribution, soil protection and flood prevention, pollutants filtering and sheltering species, essential for climate and water cycle regulation.
- Within this thesis, the relation between the NEN components and environmental service benefits were presented. Thus, the NEN can be used as a framework for land-use planning to counteract fragmentation of the landscape, and coupled with at-risk mapping will contribute to limit the consequences of flooding, soil erosion risks and forest fires, decreasing environmental problems and estimated costs of prevention measures. Thus, the benefits of a Portuguese NEN into a sustainable development and part of a (broader) nature base solutions (NBS) by increasing the ecosystems quality and become less dependent on economic and social activities, helping in the restoration of degraded ecosystems and environmental risk prevention.

Land Morphology concept and mapping method

Land Morphology (LM) is used to define the landscape form that arises from its dominant physical structures, linking together the topological and hydrological features. The LMC provides a means to classify the wet and dry systems in the hillslope profile, and supports an understanding of ecological functioning by classifying landforms according to their hydrological condition.

- The LMM method relates topographic and physical characteristics of the landscape and identifies and maps, with sufficient detail, wet and dry systems. (1) The WS includes permanent and temporary streams, water bodies, wetlands and valley bottoms. Valley bottom is a broad concept which comprehends not only floodplains but also flat and concave areas, contiguous to streams, in which slope is less than 5 %; (2) The dry system includes hillslopes and hilltops (ridges and large hilltops).
- The LM mapping method, based on flat areas (slopes less than 5 %), surface curvature and hydrological features, was applied at national level. The 25 m spatial resolution GIS map of mainland Portugal's land morphology and landforms elements accurately depicting the wet and dry systems with cartographic details at this level of scale didn't exist previously;
- By specifically distinguishing valley bottoms and hilltops from flat areas, an atypical practice in landform classification, this method is a helpful evaluation tool for modelling natural systems, namely floodplains, across regions and countries (simply by modifying the slope gradient).

Land Morphology and flood risk mapping

Mapping the wet system at national level may have an impact on clarify concepts related to water resources and can be used as a preliminary delimitation of floodplains and potential flood risk areas.

- The land morphology (LM) approach identified and mapped all river ecosystems, at the national level. This morphological approach is less demanding data and time-consuming than hydrological methods and can be used as the preliminary delimitation of floodplains and potential flood risk areas, especially where there is no, or limited, available hydrological data for all river basins to map floodplains and flood risk areas.
- Consequently its introduction to mainstream flood mapping poses significant value for the European Union encompassing the /60/EC 2000Water Framework Directive and 2007/60/EC Floods Directive, and the Portuguese Government, namely it may support the current definition and mapping of flood areas in the Portuguese Ecological Reserve;
- A river basin study contributed to a better understanding of the basin morphology at a local-scale and the effects of soil sealing in downstream flood risks. Additionally, the LM map can be easily used as a valuable complementary tool for land-use planning that coupled with flood risk mapping will contribute to limit the consequences of flooding.

Contributions to science and society

[“I mean, planning, obviously, is a most important human activity. Planning concerned with survival, and successful adaptation (…) is going to work when it stops becoming the exclusive preoccupation of a very small number of professionals” (McHarg, 1992).] In this sense, this thesis gives significant contribution to increasing the awareness of spatial and functional variety of EN within GI planning approach by:

- Enhancing the notions of connectivity, multi-functionality, continuity and infra-structuring character of the landscape. It also relates ecological components with ecosystem services that provide value to ecological functions, often to the direct benefit of human populations in health, economic or social terms that may hold a key position by enabling planners to develop attractive and functional spaces that promote multi-functional use within all scales of policy.

- It can be seen as the building block for landscape planning and management instruments at the national, regional and municipal levels. Providing a major contribution to the upcoming Portuguese GI, which is to be implemented between 2014 and 2020, in order to accomplish the EU “GI Strategy”, integrating higher-level based planning EU’s main policy, especially Water Framework Directive and Floods Directive, EU Common Agricultural Policy and Natured-based solutions.

- It may also be used to integrate the Portuguese environmental policies more effectively, namely to National Program for Land Planning Policy (PNPOT), the Fundamental Network of Nature Conservation (RFCN), the National Ecological Reserve (REN), National Agricultural Reserve (RAN) and Public Hydric Domain (DPH) and Nature Conservation Areas (NSCA).

- At the same time, the NEN data layers and EN mapping method can be replicated internationally, just by modifying the ecological thresholds relative to local conditions; and detailed at regional and municipal scales, solving the EN criteria problem, the schematic representation of the networks and the cross-border coherence at regional and municipal levels.

- A significant contribution was the production of new maps to overcome missing data, namely a unified soil map for the whole country, a land morphology map comprising all the river ecosystems and floodplains for mainland Portugal (Cunha et al., 2017). Simultaneously, the NEN components were assessed individually, according to ecological value, revealing specific ecological functions, directly influenced by hydrologic availability, soil genesis processes and fertility, plant biodiversity (species) and habitat resources.

- Moreover, it addresses the lack of mapping at the national level of ecological systems since all maps resulting from the NEN project are available online and free for download in a web platform

EPICWEBGIS, available at http://epic-webgis-portugal.isa.ulisboa.pt/. This might have an implication in the future planning system by overcoming missing data on soils, water and vegetation, and can be seen as an instrument to support further academic research, planning teams, practitioners and policy makers providing an understanding of the multivariate and multi-criteria factors helping to "create actual and new GI at the delivery level".

Future research

- In future work the cultural functions of the landscape should be included in the NEN methodology in articulation with the different sectors of GI, to improve delivery of ecosystem services and to integrate benefits for biodiversity with socio-economic interests;

- Increase the dialogue between planners, government agencies, politicians and decision makers, stakeholders and the citizens, promoting the role of EN regarding the value of "green" infrastructure; Elaborate a government guidance for GI that proposes its use as a mandatory element of planning and its articulation of policy;

- Improve the communication/marketing and funding of GI at implementing level. GI should be identified as being as important as other infrastructures;

- As happening in other countries, EN should be integrated into other initiatives that mutually benefit environmental protection and economic growth as "environmental compensation" (Küpfer, 2008). Quantifying the economic benefits of the ecological services provided by EN and GI, in order to measure GI implementation success.

Finally, this research highlights the importance of the design into landscape management and the NEN and LM as ecologically based planning tool, which provide kwnoledge that contributes to improve the management of natural risk protection and resilience building, whilst also enhancing landscape aesthetics and an appreciation of Portuguese natural heritage, whether in urban or rural areas. It contributes to the understanding of the NEN more purposeful than restrictive planning tool which provides basic knowledge to support and forecast how human activities could modify spatial connections and the environmental impacts associated with the ecological resources/ ecosystems services.

APPENDICES

APPENDIX A

A.1 Examples of Ecological Networks in Europe

Table A.1 and Table A.2 present an overview of the current status of national EN in countries in Europe. Adapted and updated from Jongman et al. (2004), Bennett and Mulongoy (2006), Bonnin et al. (2007) and EC (2013).

Table A.1 Ecological Networks in Europe – International level

Figure	Location	Date	Description	References
A.1	Europe	1992	**Natura 2000 network** Across biogeographical regions	EU (European Union)
A.2	World	1994	**Global Protected Areas** IUCN Categories	IUCN (International Union for Conservation of Nature) Dudley (2008)
A.3	World	1997	**The Global 200** Ecoregions Project	WWF (World Wildlife Fund)
A.4	World	2014	**A New Map of Global Ecological Land Units**	American Association of Geographers Sayre et al. (2014)
A.5 A.6 A.7	Europe	1999 - 2006 2002 2006	**Pan-European Ecological Network (PEEN)** PEEN for South-Eastern Europe PEEN for Central and Eastern Europe PEEN for Western Europe	ECNC (European Centre for Nature Conservation) Jones-Walters (2007), Jongman et al. (2011) Biró et al. (2006) Bouwma et al. (2002) Jongman et al. (2006)
A8a A.8b	22 countries	2002	**European Green Belt** Nature conservation purposes. Ecological corridor running the length of Europe with the idea of managing and preserving ecological connectivity	BUND (Friends of the Earth Germany), BfN (the German Federal Agency for Nature Conservation) and IUCN http://www.europeangreenbelt.org/ Geidezis and Kreutz (2012)
European Green Belt initiative Examples	Slovenia, Croatia, Bosnia Herzegovina Serbia	2007-2009	**Sava River Ecological Network** The protection of biodiversity of Sava River basin floodplains and the establishment of sustainable water management- pilot example for the implementation of the European Union's Water Framework Directive	IUCN and LIFE Program International Agricultural Centre Netherlands (Wageningen International) http://www.savariver.com/
	Slovakia and Austria	2009	**Alpine-Carpathian Corridor** 120 km wide ecological corridor from the Alps to the Carpathians mountain ranges.	IUCN, UNEP (United Nations Environmental Programme), Alpine and Carpathian Conventions, Province of Lower Austria
	Russia, Estonia, Latvia,Lithuania Poland	2009	**Baltic Green Belt**	EU within the Baltic Sea Region Programme Maack et al. (2012)
A.9	Europe	2015	**Green infrastructure network for Europe**	EEA (2014), EU (2015) Liquete et al. (2015) OpenNESS project

Table A.2 Ecological Networks in Europe – National level

Figure	B/E	Location	Date	Description	References
A9	**B**	Belarus	1995	**Belarus National EN**	Baranets and Yurgenson (1998)
-		Belgium**	2007	Region scale maps, e.g. **Flanders - Flemish EN** **Wallonia - EN of Walloon** **Brussels - 'Green Network' 2002**	Bennett (2010)
A.10	**B**	Croatia	2002- 2005	**Croatian national EN** **CRO-NEN Project**	LIFE III program State Institute for Nature Protection
A.11	**B**	Cyprus	1999 -	**Cyprus Natura 2000**	EU Natura 2000
A.12	**E**	Czech Republic*	1996 - 2005	**Czech Territorial System of Landscape Ecological Stability**	Agency for Nature Conservation and Landscape Protection Kubeš (1996) Václav and Plesník (2009)
-	-	Denmark	2008	**Nature Network**/ *Naturverbindsele*	Danish Nature Agency Danish Society for Nature Conservation Goldberg (2008)
A.14 A.15	**E**	Estonia	1983 2010	**Network of Compensative Areas** Estonia Green Network - vision 2010 Green Infrastructure - Estonia 2030	Jagomägi et al. (2000) Külvik et al. (2008), Raet et al. (2010)
A.16 A.17	**E**	France**	2007	**Green and Blue Network**/ *Trame Verte et Bleue* Regional scale maps, e.g. **Sologne region**	http://www.trameverteetbleue.fr/ Grisard et al. (2000)
A.18	**B**	Germany **		**Biotope Network**/ *Vernetzter Biotopsysteme, Rheinland-Pfalz*	BfN (the German Federal Agency for Nature Conservation) Leibenath et al. (2010); Riecken and Finck (2012)
A.19	**B**	Hungary	1995 2002	**Hungarian national EN**/ *Nemzeti Ökológiai Hálózat*	IUCN http://www.foek.hu/korneteng/nen.htm
A.20	-	Italy**	-	Region scale maps, e.g. **Reti Ecologiche Regionale** Lombardia **Central Apennines** - Planeco Project	University of Aquila http://www.isprambiente.gov.it/ Franco (2004)
A.21	**E**	Ireland	2000	**Ireland Green Infrastructure**	https://www.epa.ie/ O'Riain et al. (2010), Lennon (2014)
A.22	**B**	Lithuania*	1980 2010- 2014	**Nature Frame** e.g. Pilot case of EN through Nature Frame areas in South Lithuania	Jongman et al. (2004) LIFE+ Program, Ministry of Environment of the Republic of Lithuania Mierauskas and Palaima (2012)
A.23	**B**	Macedonia	2011	**Macedonian national EN**	Macedonian Ecological Society Brajanoska et al. (2009)
A.24	**E**	The Netherlands	1990 2014	**Dutch National ecological network** *Ecologische Hoofdstructuur*	Jongman and Bogers (2008)
A.25	**B**	Poland		**National ECONET**	IUCN Liro et al (1995)
A.26	**B**	Portugal	2007	**No EN map at national level** Region scale maps **(ERPVA)**	DGOTDU (2007) Projects initiated by universities and NGOs in cooperation with municipal authorities
A.27	**E**	Slovakia*	1996	**Territorial System of Ecological Stability** **National EN of Slovakia – NECONET**	IUCN and Institute of Landscape Ecology, Slovak Academy of Sciences (ILE-SAS) Miklós (1989)
-	-	Spain**		Region scale maps, e.g. **EN of Barcelona Metropolitan Area** (Ecological Connectivity Index)	Marulli and Mallarach (2005)
A.28	**E**	Switzerland	2004	**Swiss National Ecological Network** Réseau écologique national	Berthoud et al. (2004)
-	-	UK**		Region scale maps,e.g **Somerset's Ecological Network** **Cheshire ECOnet**	DEFRA (Department for the Environment, Farming and Rural Affairs),Natural England Catchpole (2008)

E – Ecological approach; B – Biological approach
* Legislation: Ecological Network is the core of nature conservation legislation.
** Actual responsibility for nature conservation is not at the national level but at the regional or federation level

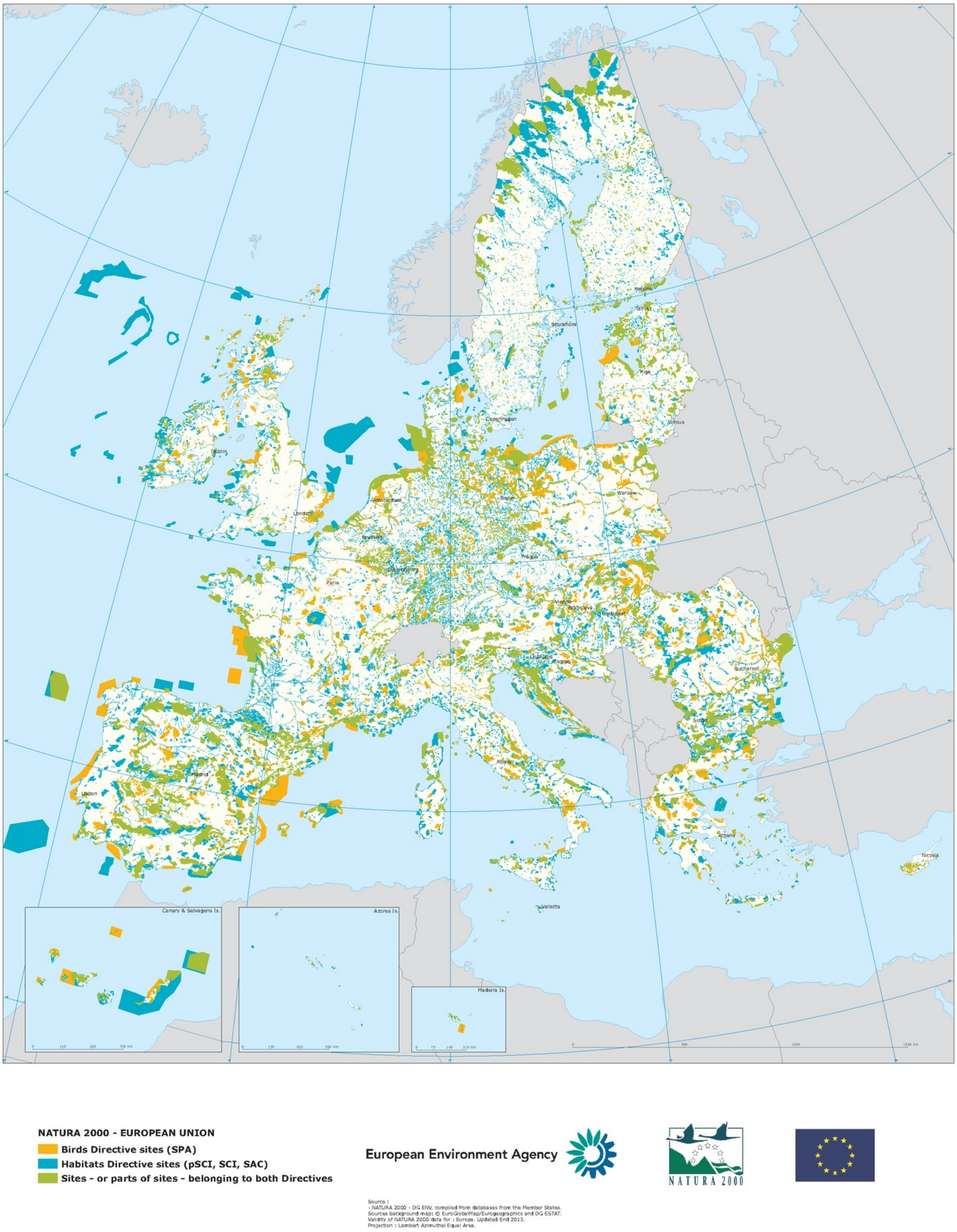

Figure A.1 Natura 2000 network - Birds and Habitats (EU, 2015).
Available at http://www.eea.europa.eu/data-and-maps/figures/natura-2000-birds-and-habitat-directives-7/eu28-birds-and-habitats-directives/

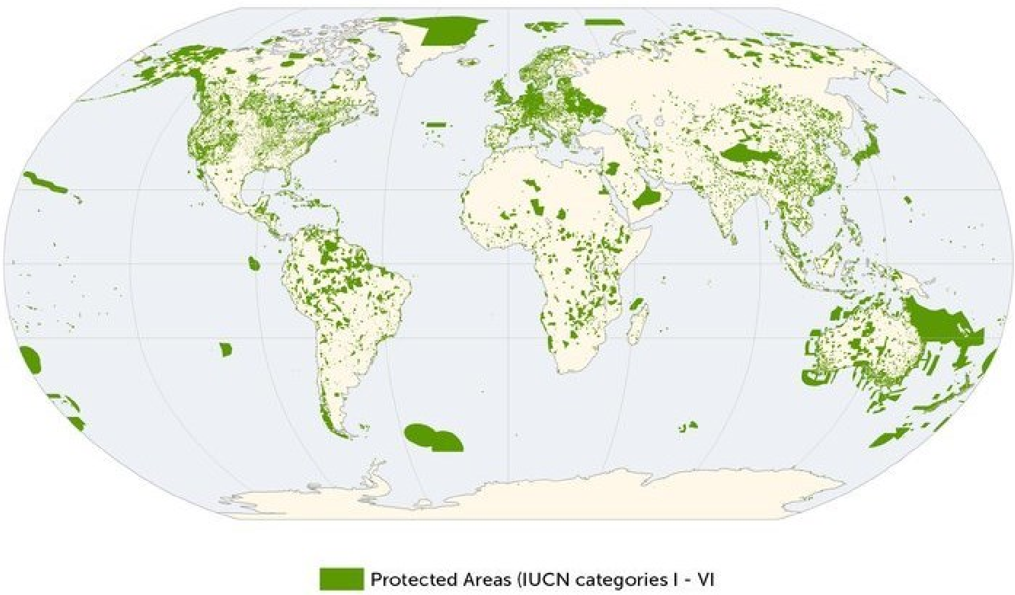

Figure A.2 Global protected areas map (IUCN and UNEP-WCMC, 2014).
Available at http://www.biodiversitya-z.org/content/iucn-protected-area-management-categories

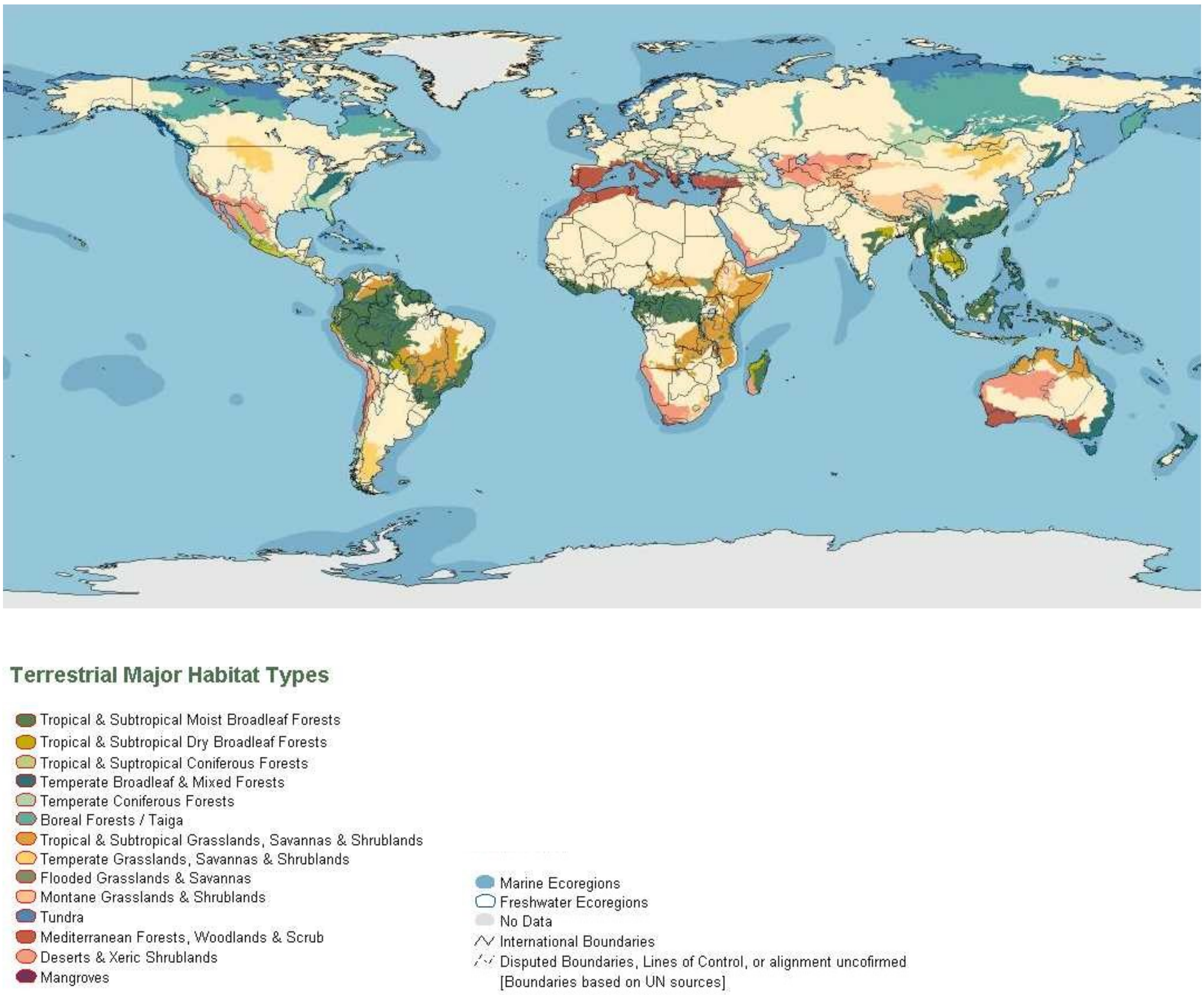

Figure A.3 G200 Ecoregions Project – 14 Terrestrial major habitat types (WWF, 2000; Olson et al., 2001).
From all ecoregions: 142 terrestrial, 53 freshwater, and 43 marine ecoregions. Retrieved from http://wwf.panda.org/about_our_earth/ecoregions/maps/

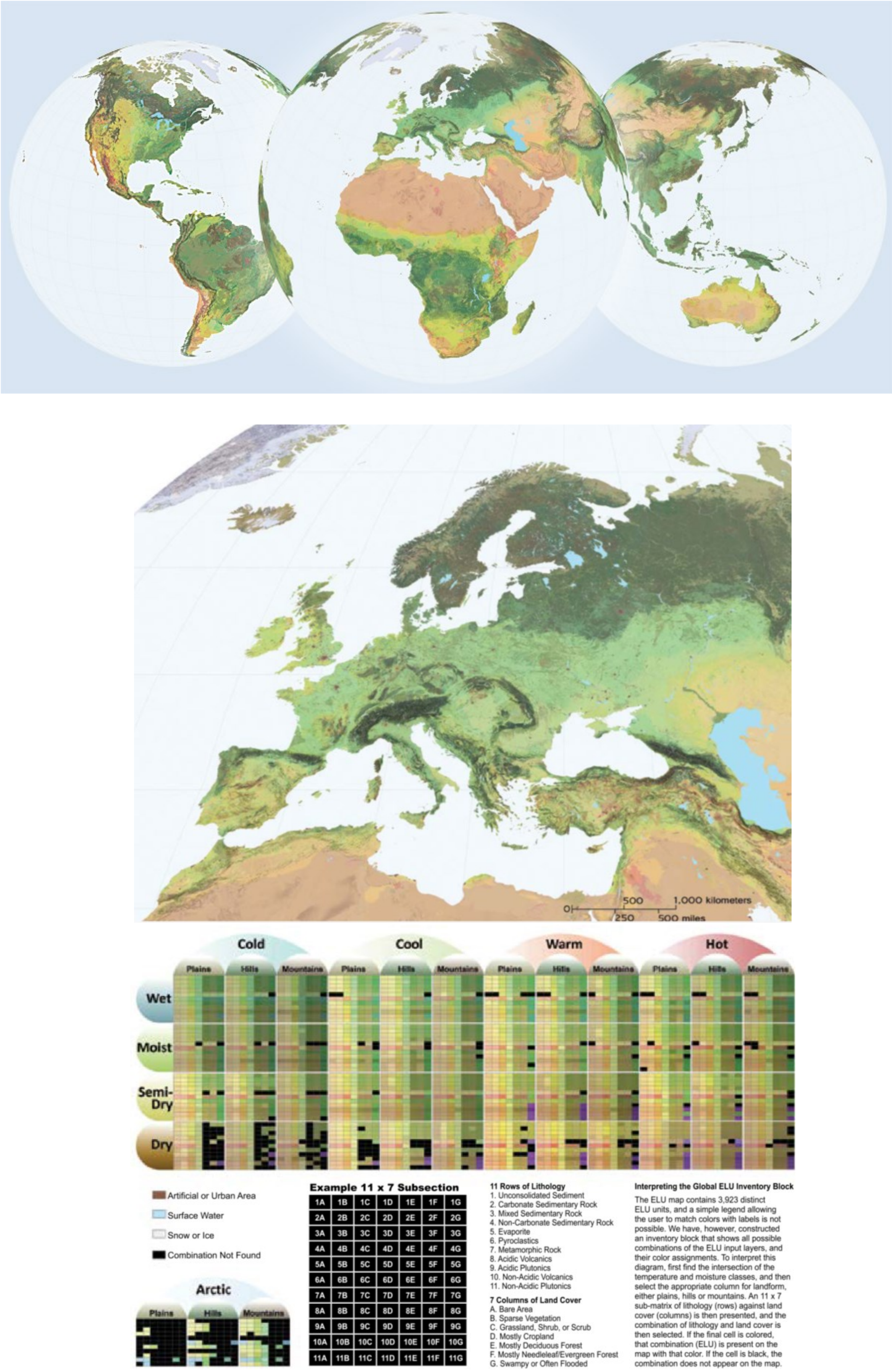

Figure A.4 A New Map of Global Ecological Land Units – An Ecophysiographic Stratification Approach (Sayre et al., 2014).

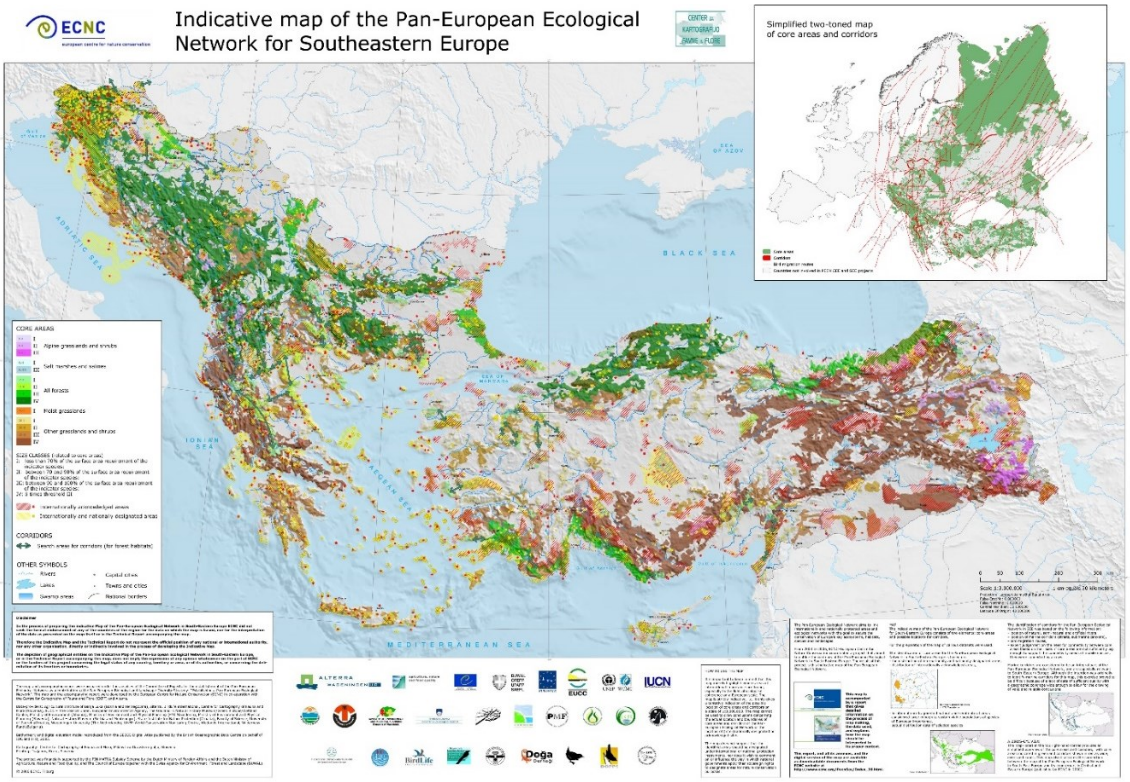

Figure A.5 **PEEN Southeastern Europe (Biró et al., 2006).**

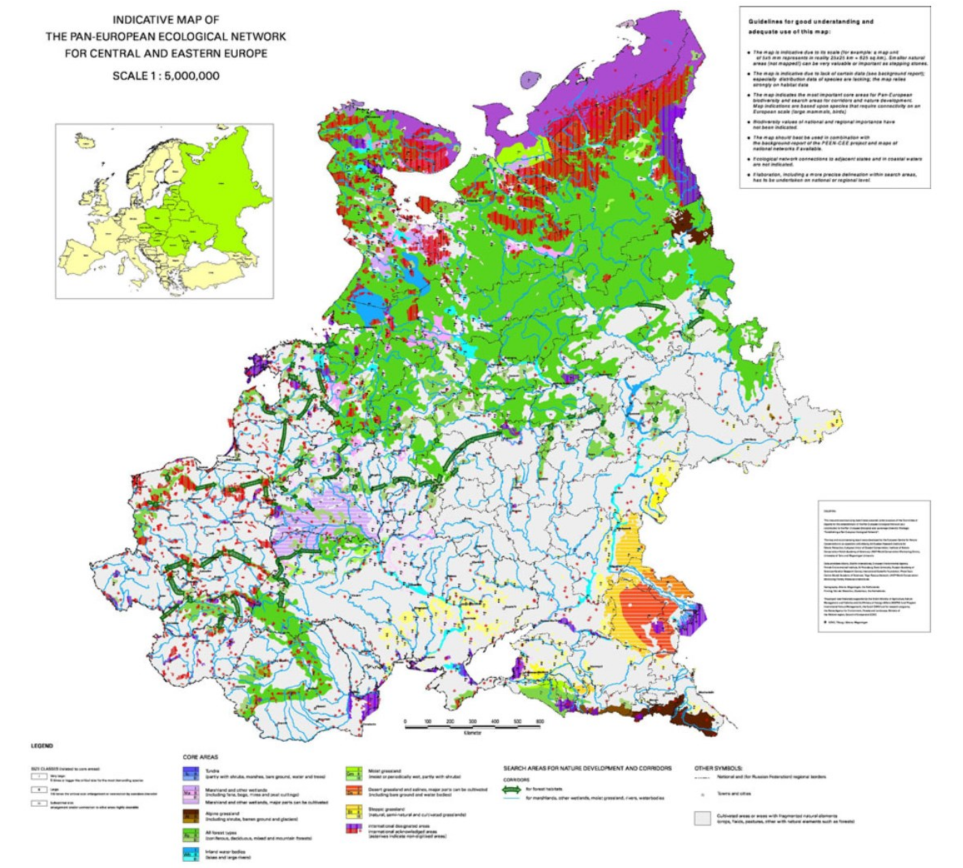

Figure A.6 PEEN Central and Eastern Europe (Bouwma et al., 2002).

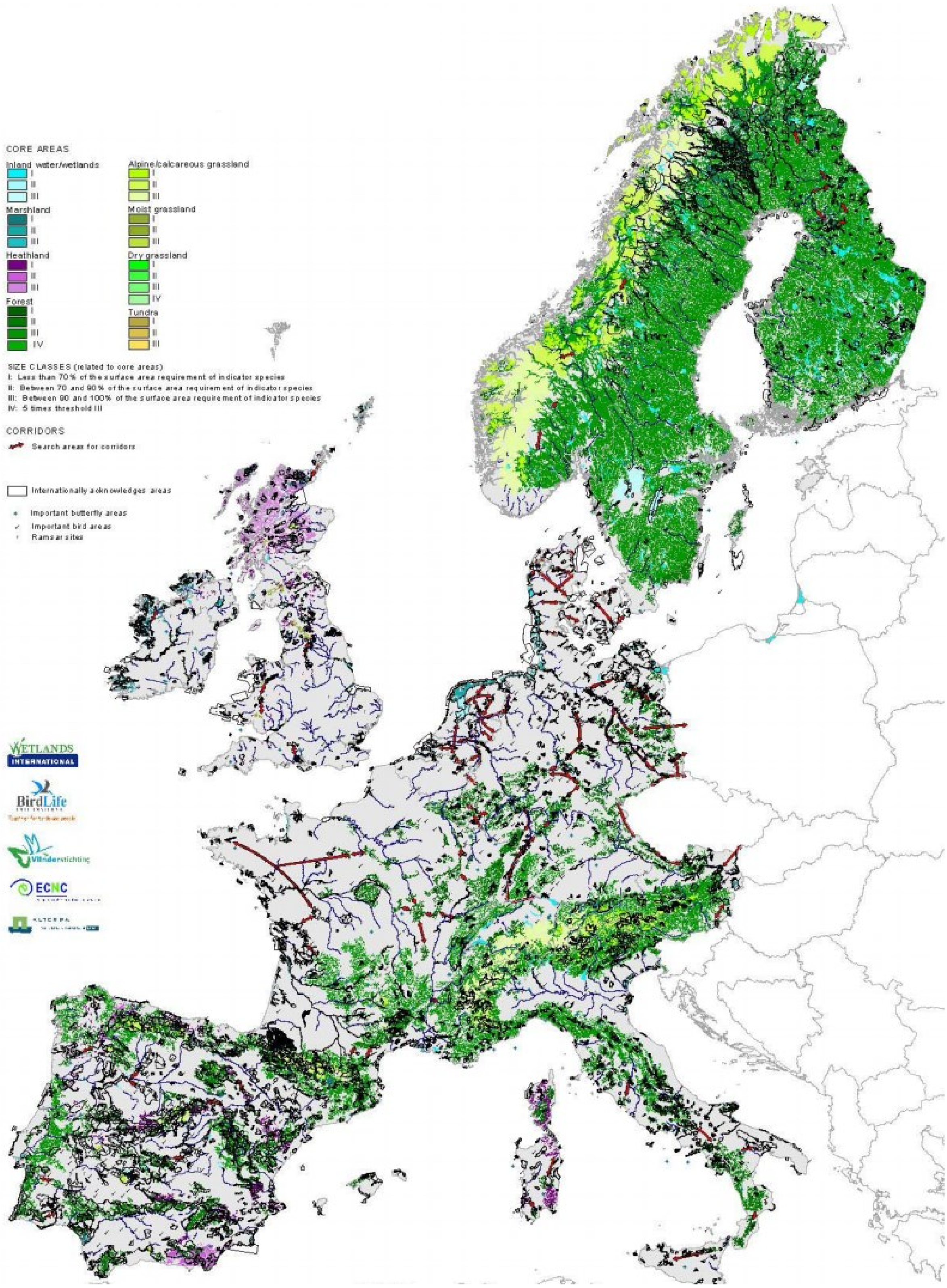

Figure A.7 PEEN Western Europe (Jongman et al., 2006).

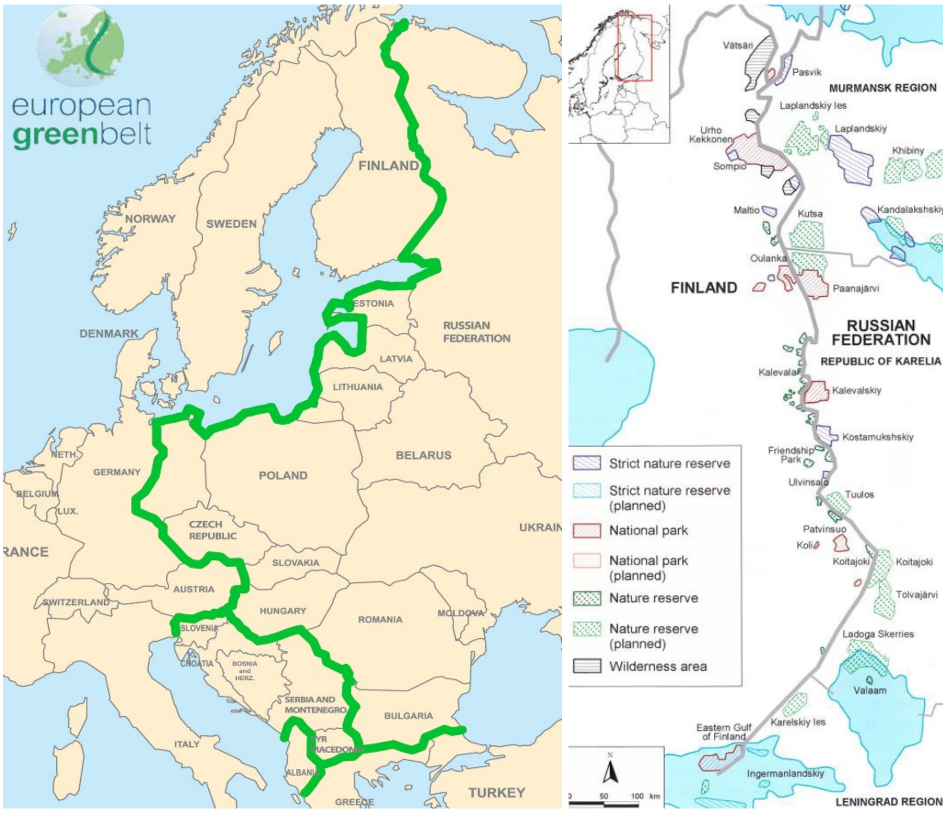

Figure A.8 (a) The European Green Belt; (b) Existing and planned nature reserves along the Fennoscandian Green Belt (Geidezis and Kreutz, 2012).

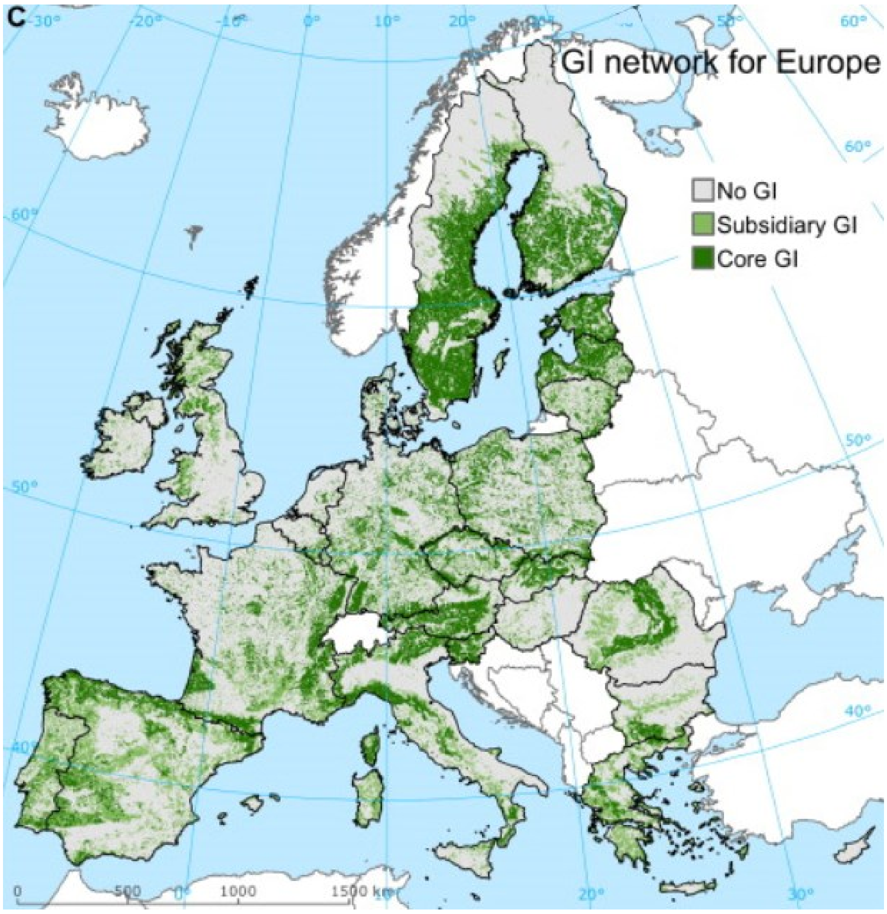

Figure A.9 Green infrastructure network for Europe (Liquete et al., 2015).

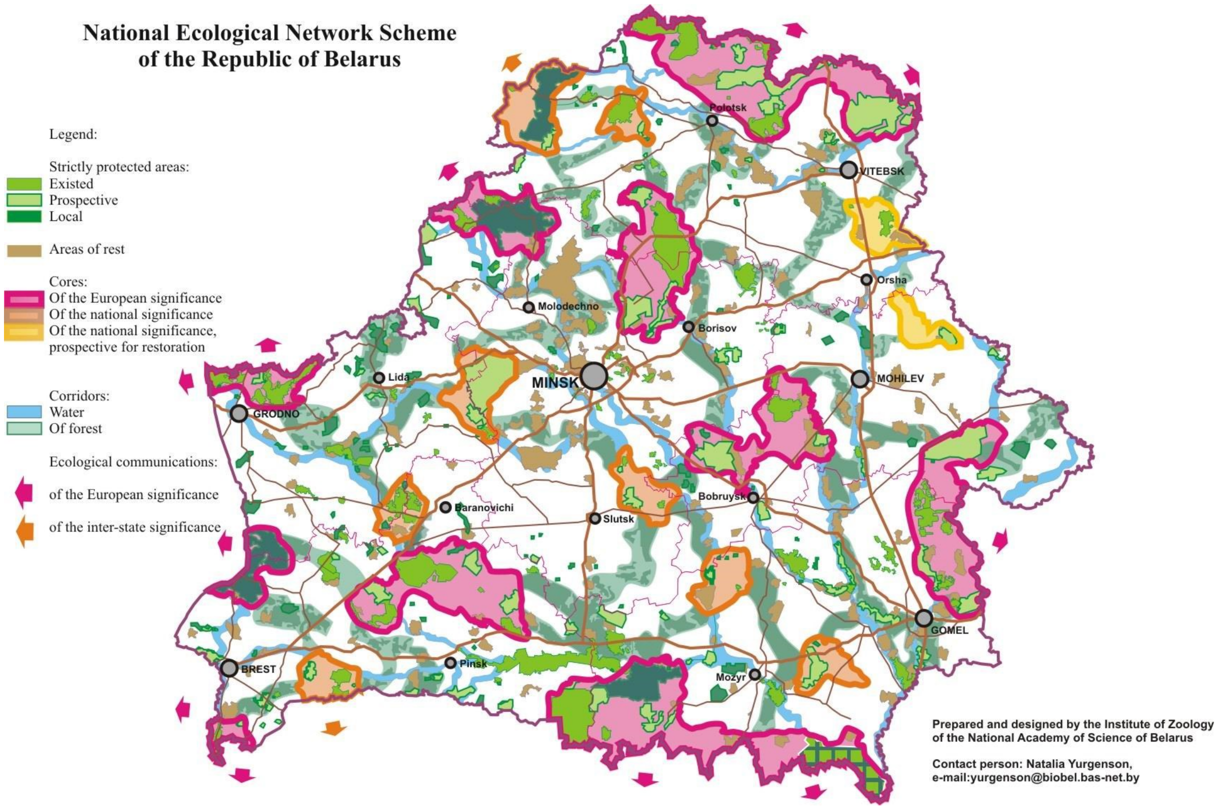

Figure A.10 Belarus National Ecological Network Baranets and Yurgenson (1998).

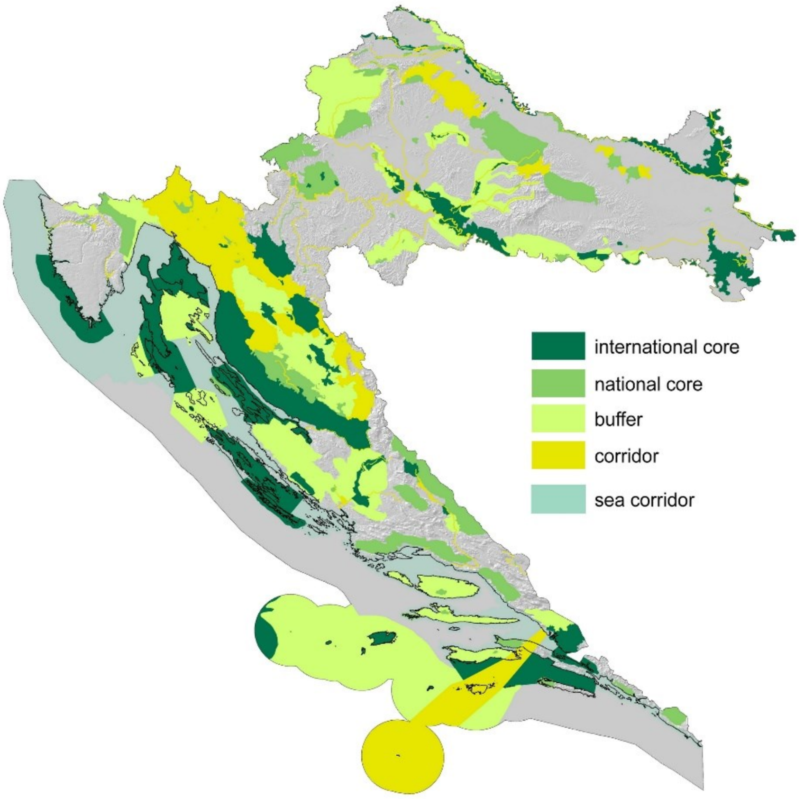

Figure A.11 Croatia National Ecological Network. Available at http://www.ecologicalnetworks.eu/

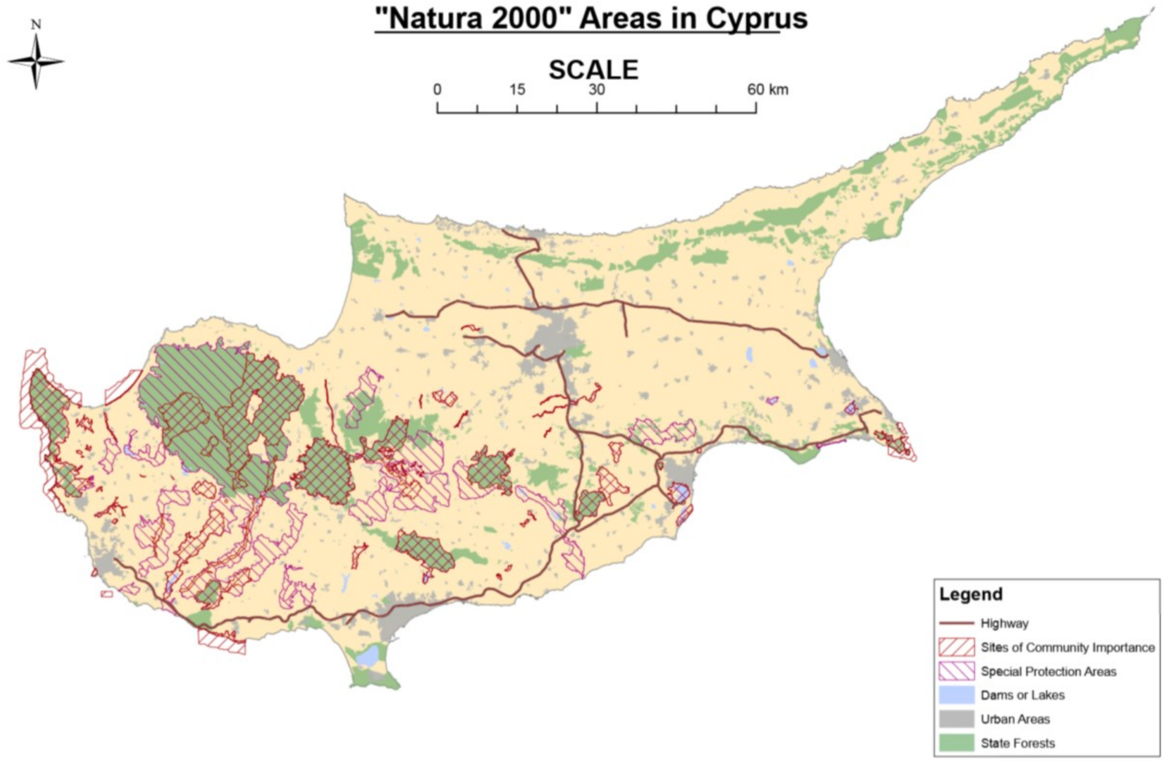

Figure A.12 Cyprus – Natura 2000 and state forest (EU, 2009)

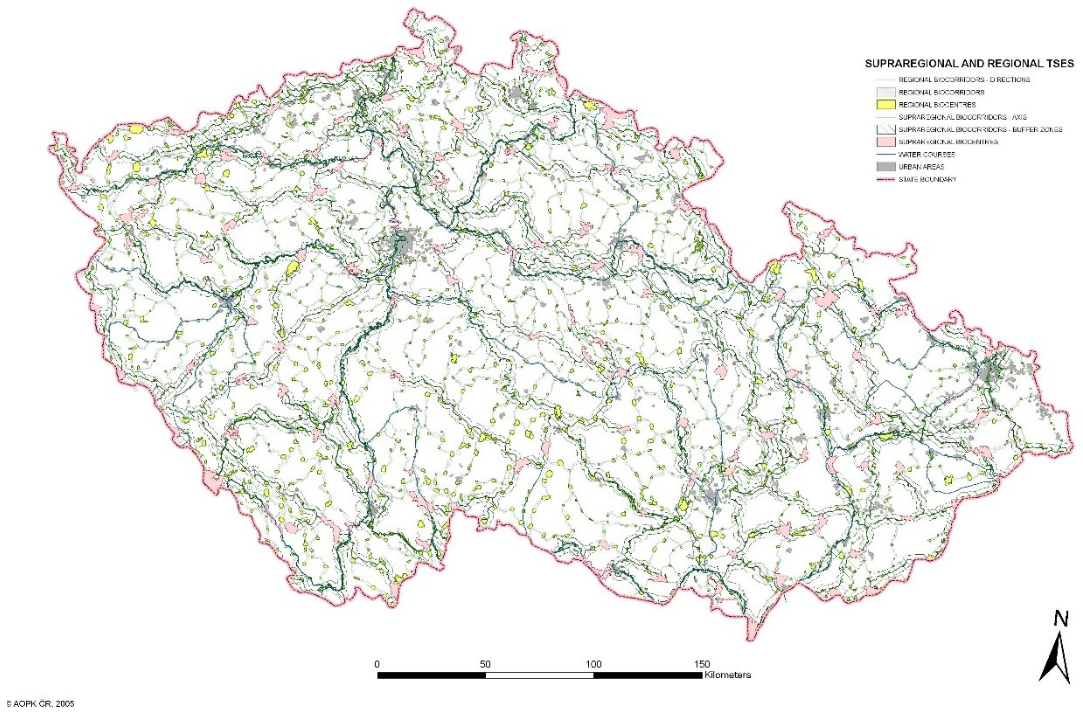

Figure A.13 Czech Republic National Ecological Network (2005). Available at http://www.ecologicalnetworks.eu

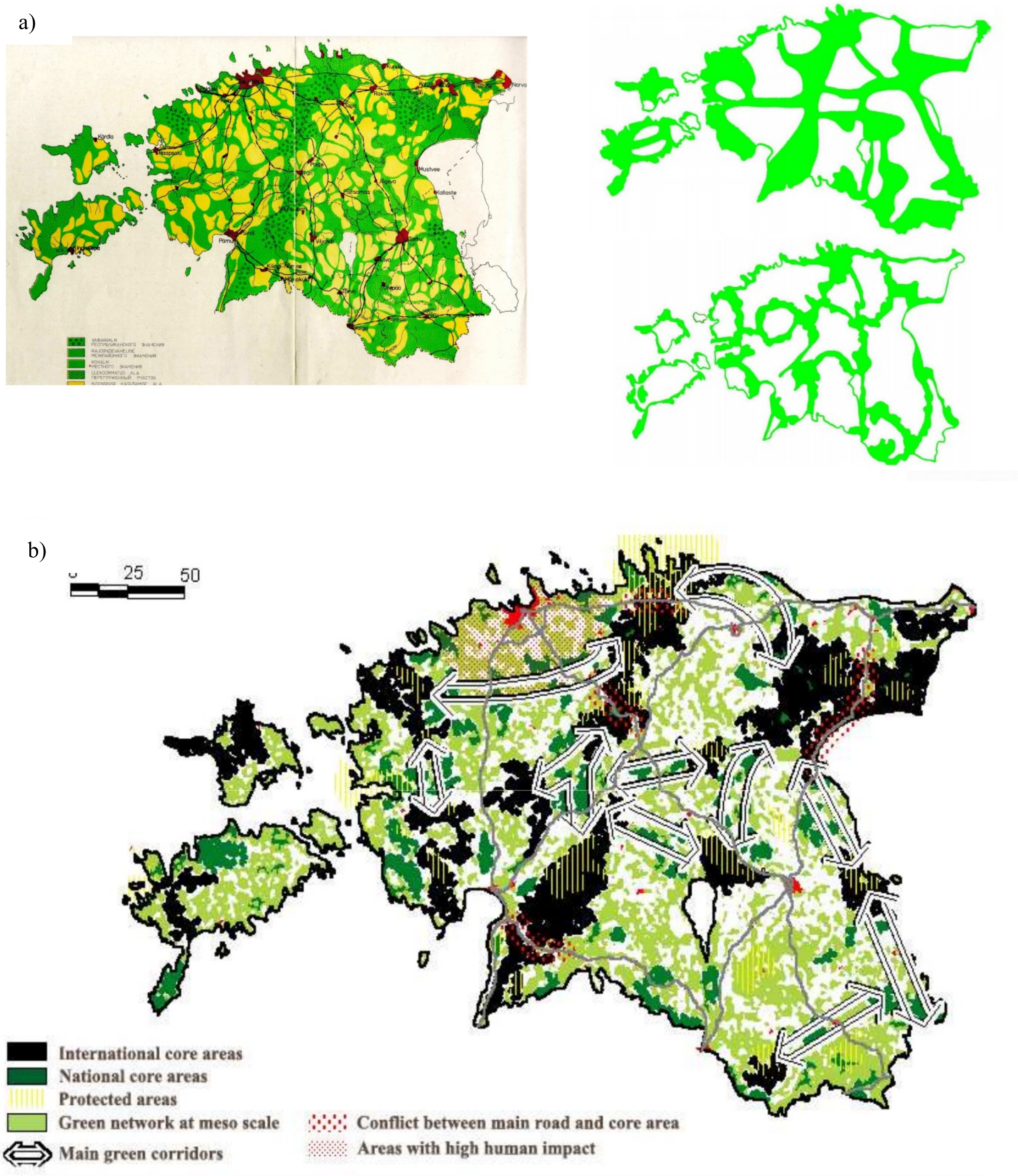

Figure A.14 a) Estonian Spatial Planning 1983 - Network of compensating areas at scale 1/200 000 b) Estonian Green Network according to "Estonia – vision 2010" (Jagomägi et al., 2000)

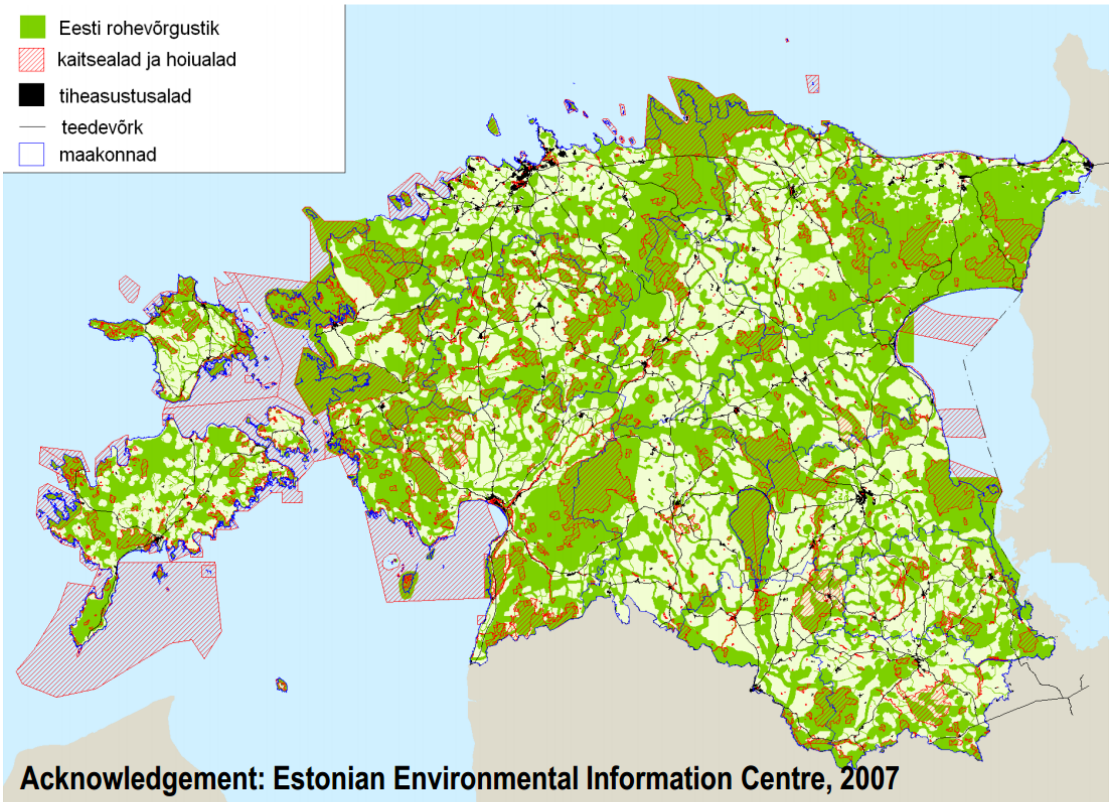

Figure A.15 Estonian Ecological Network – The legal EN compiled from 15 Green Network plans prepared at county level (2001-2007) (Raet et al., 2010; Sepp and Jagomägi, 2011)

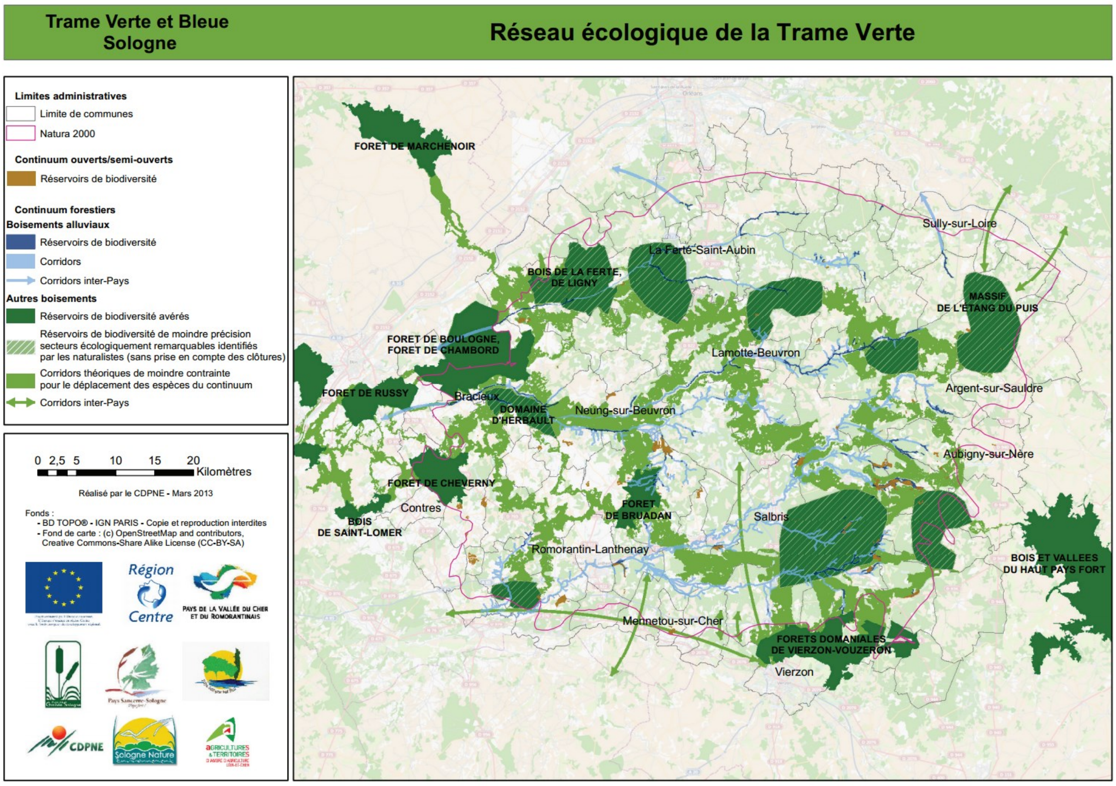

Figure A.16 Ecological Reserve of the Green Network - Sologne region (Grisard et al., 2000).

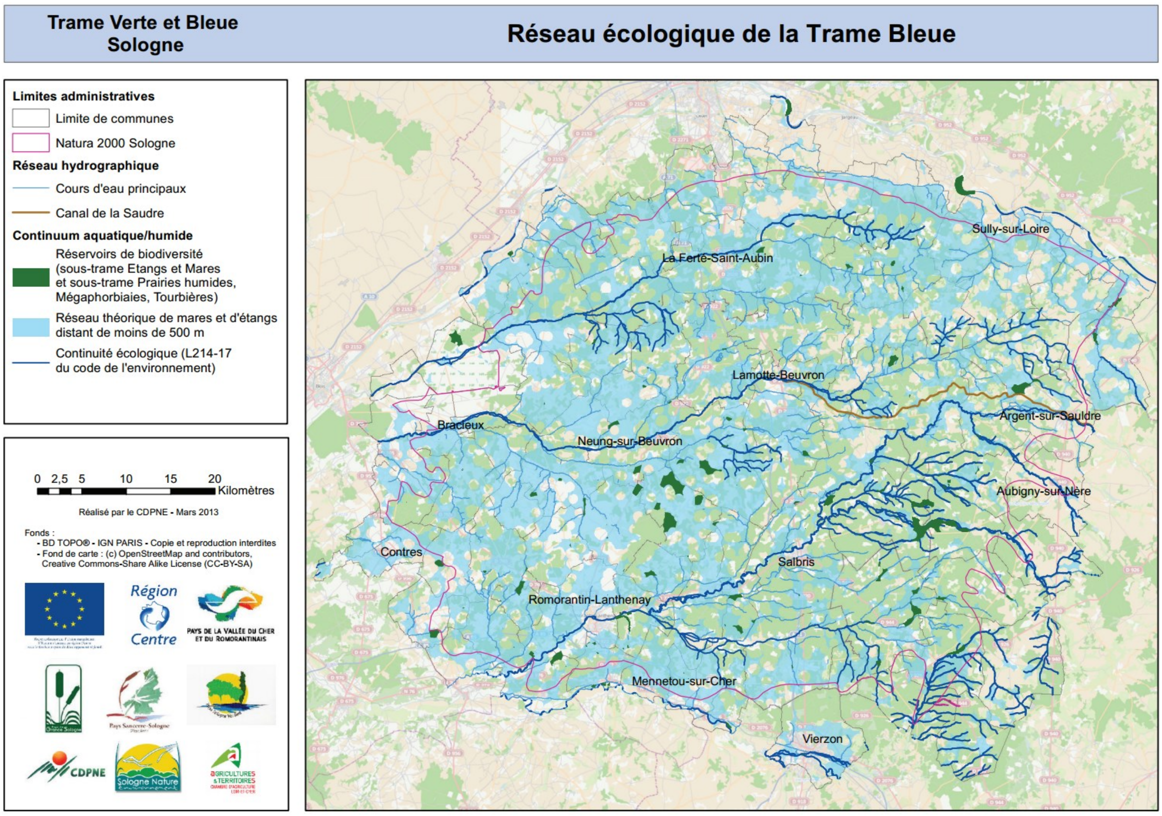

Figure A.17 Ecological Reserve of the Blue Network - Sologne region (Grisard et al., 2000).

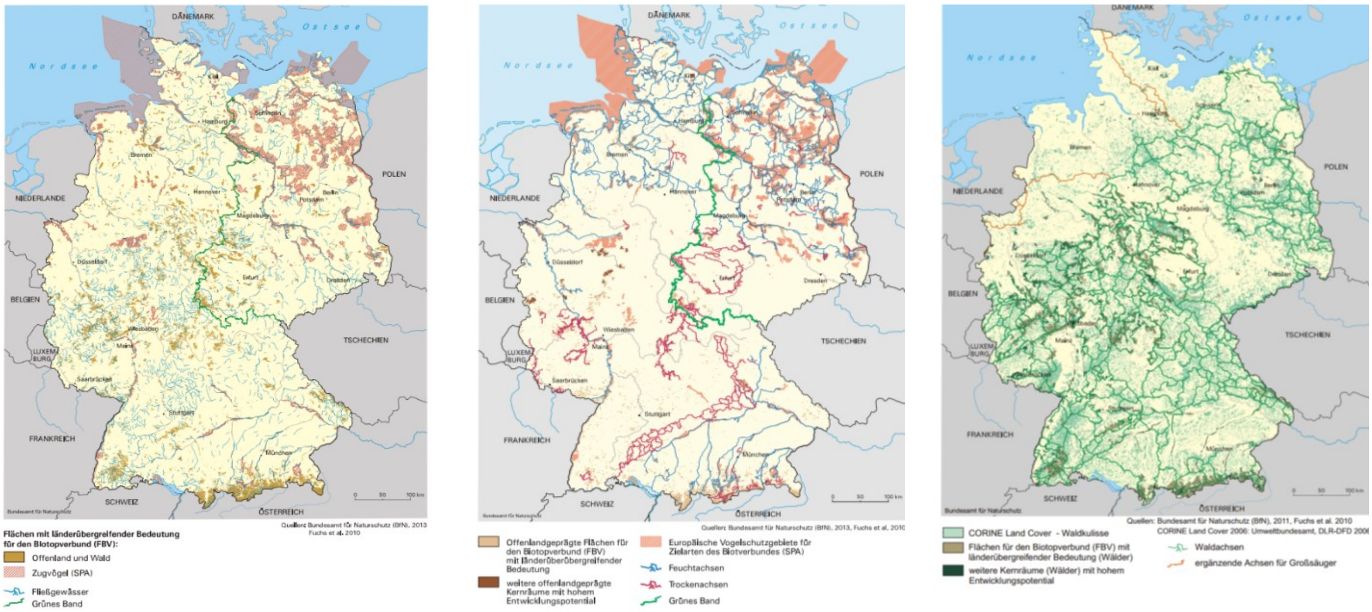

Figure A.18 a) German nationally significant areas for the ecological network 2013, b) National ecological network for open landscape habitat complexes, c) National ecological network for woodland habitat complexes (Riecken and Finck, 2012).

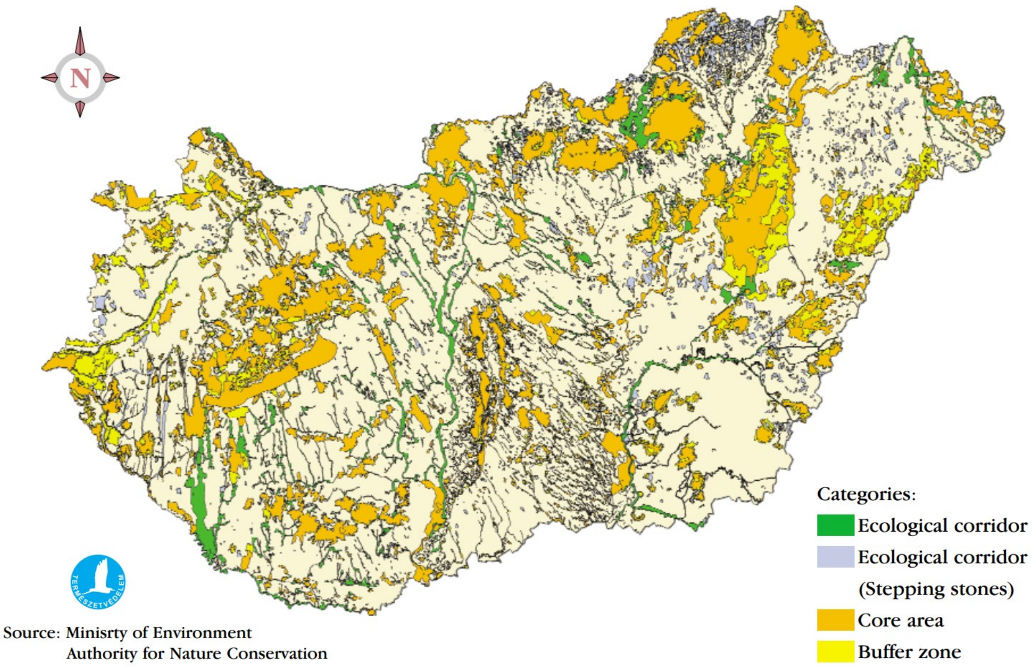

Figure A.19 Hungarian National Ecological Network (2002). Available at http://www.termeszetvedelem.hu/

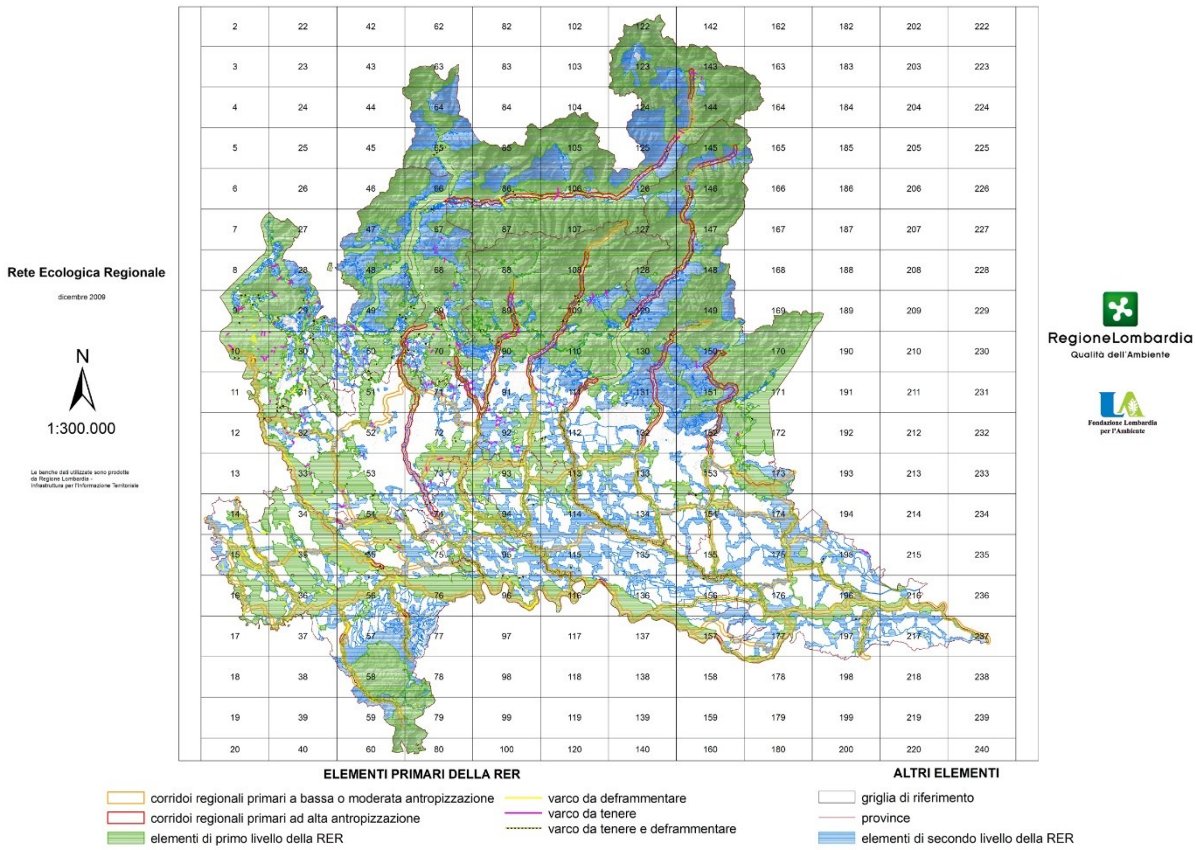

Figure A.20 Italia Rete Ecologica Regionale Lombardia. Available at http://www.flanet.org/it/553/progetto/rete-ecologica-regionale

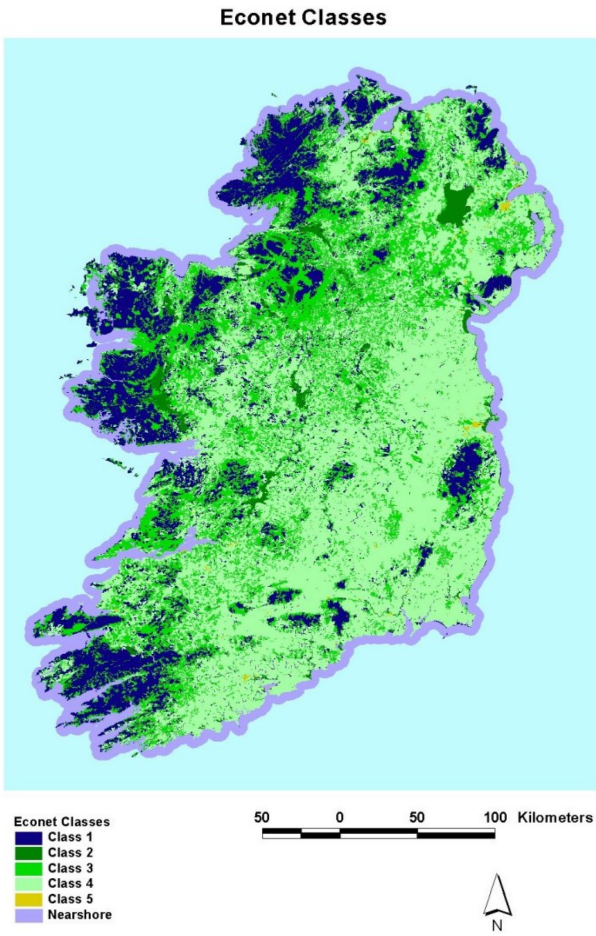

Figure A.21 Ireland multifunctional Green Infrastructure –Econet classes. Available at www.epa.ie

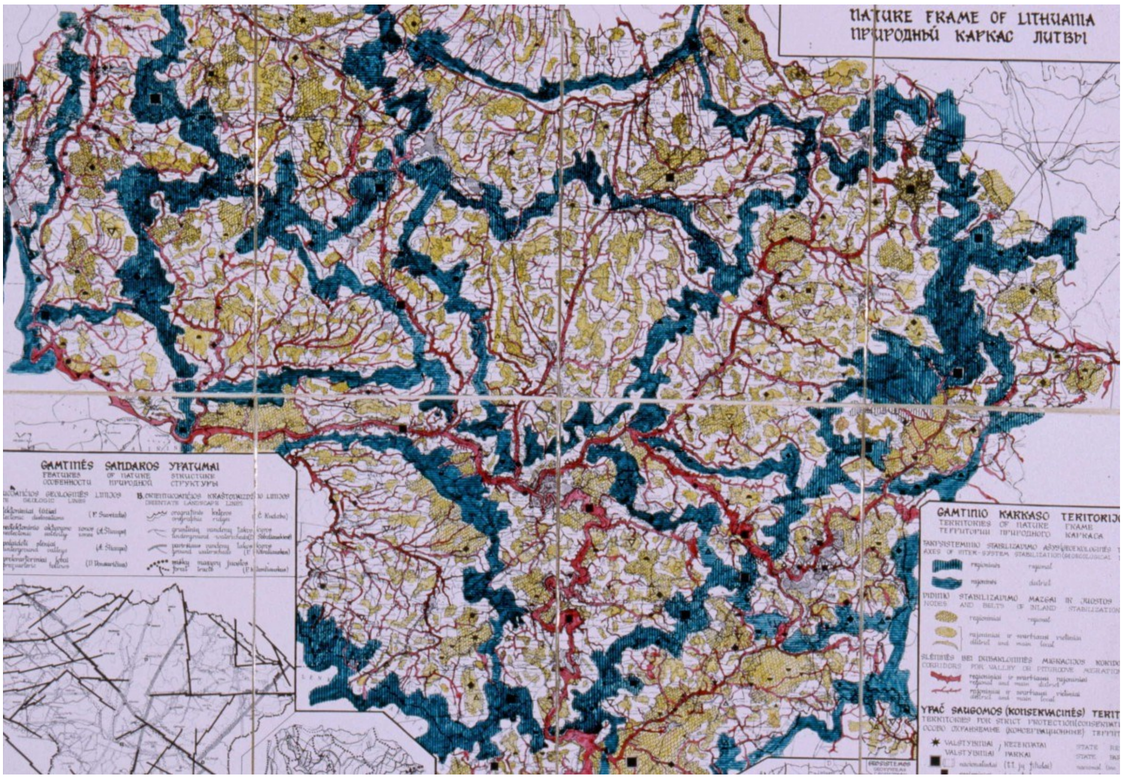

Figure A.22 Lithuania Nature Frame 1980 (Kavaliauskas, 1995 in Jongman et al., 2004).

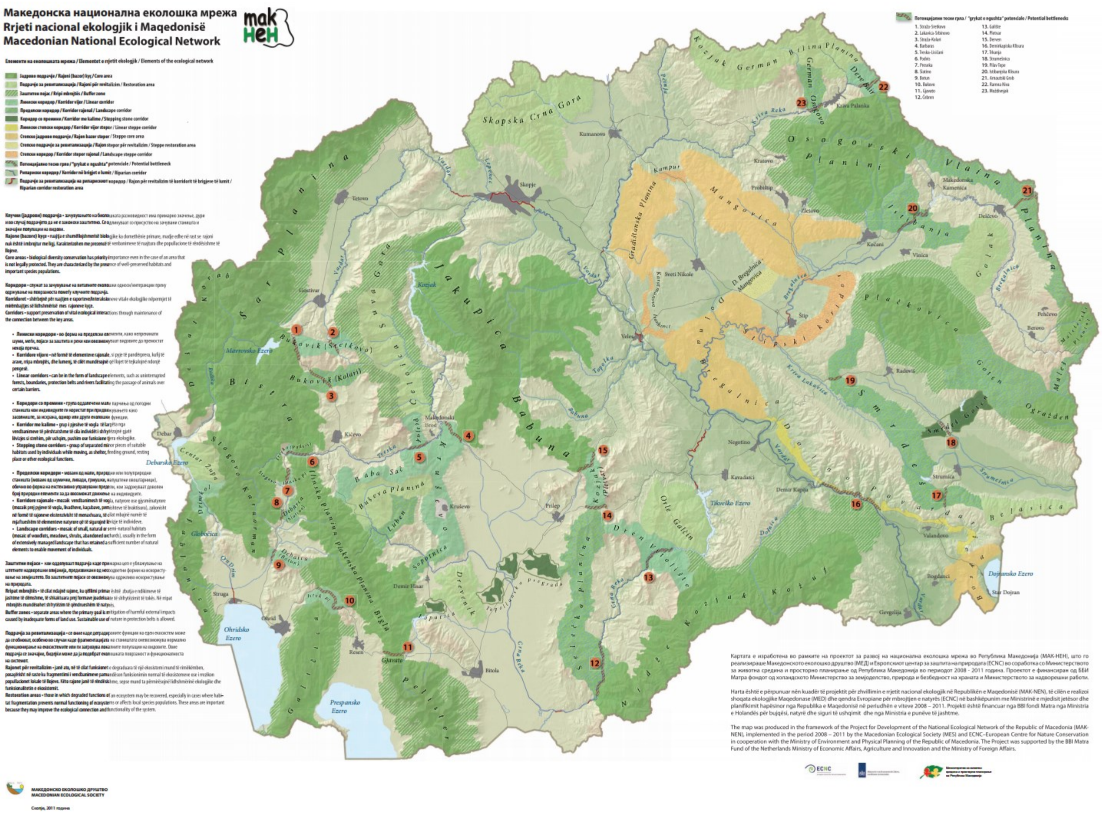

Figure A.23 Macedonia Ecological Network. Available at http://www.ecnc.org/uploads/2012/10/mak-nen-map.pdf

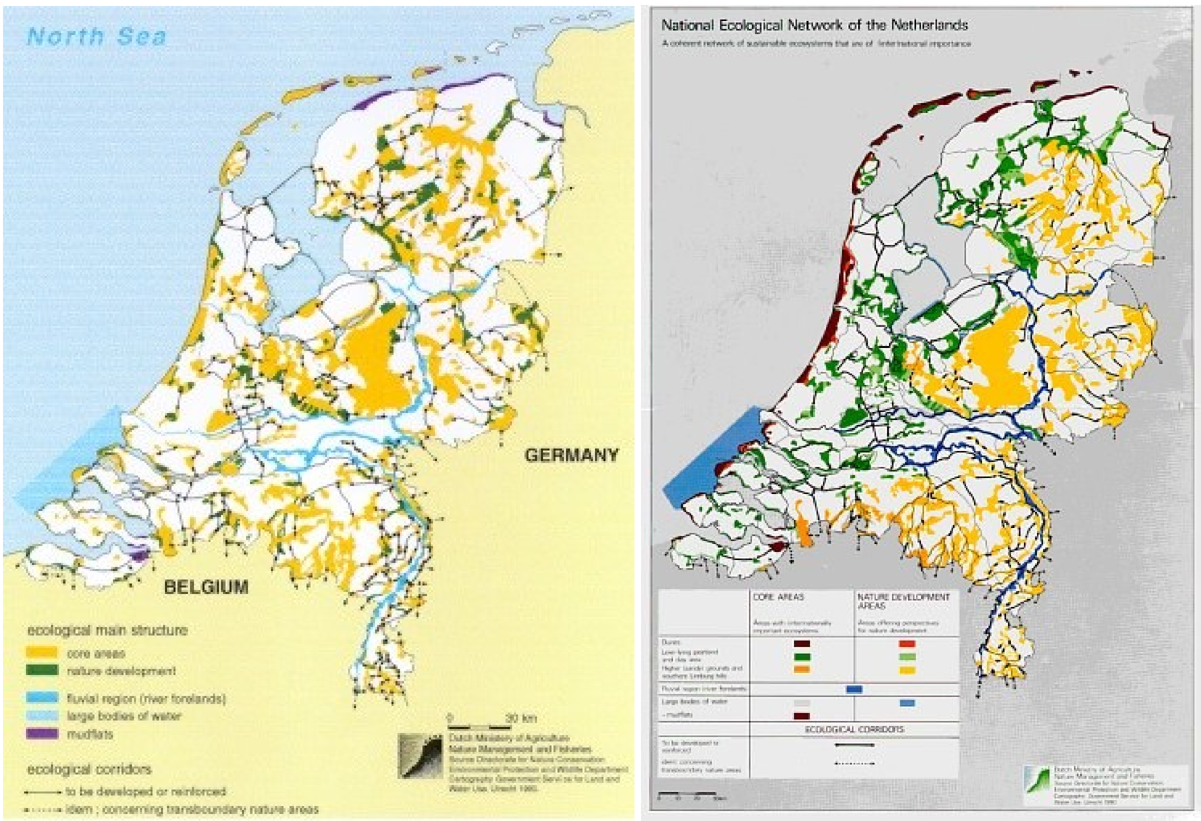

Figure A.24 Dutch National Ecological Network a) Nature Policy Plan 1990; b) National Ecological Network 2018 (Available at Jongman and Bogers, 2008).

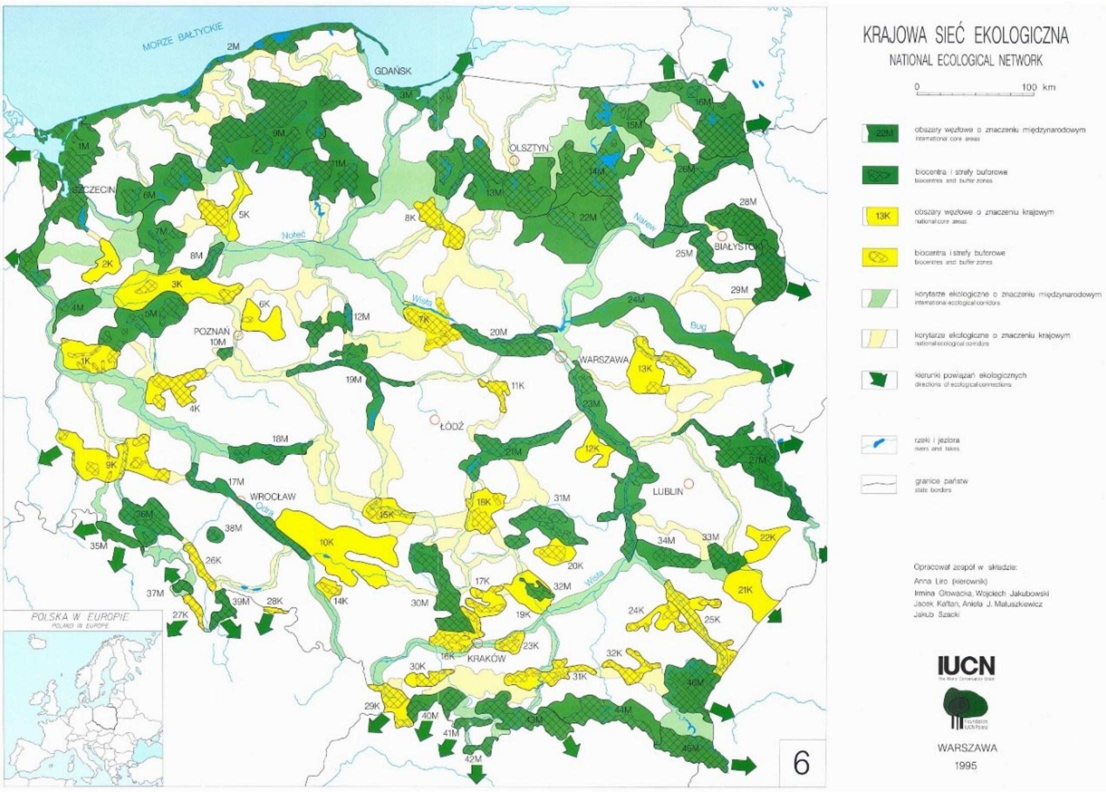

Figure A.25 Poland National Ecological Network ECONET. Available at http://www.ecologicalnetworks.eu/

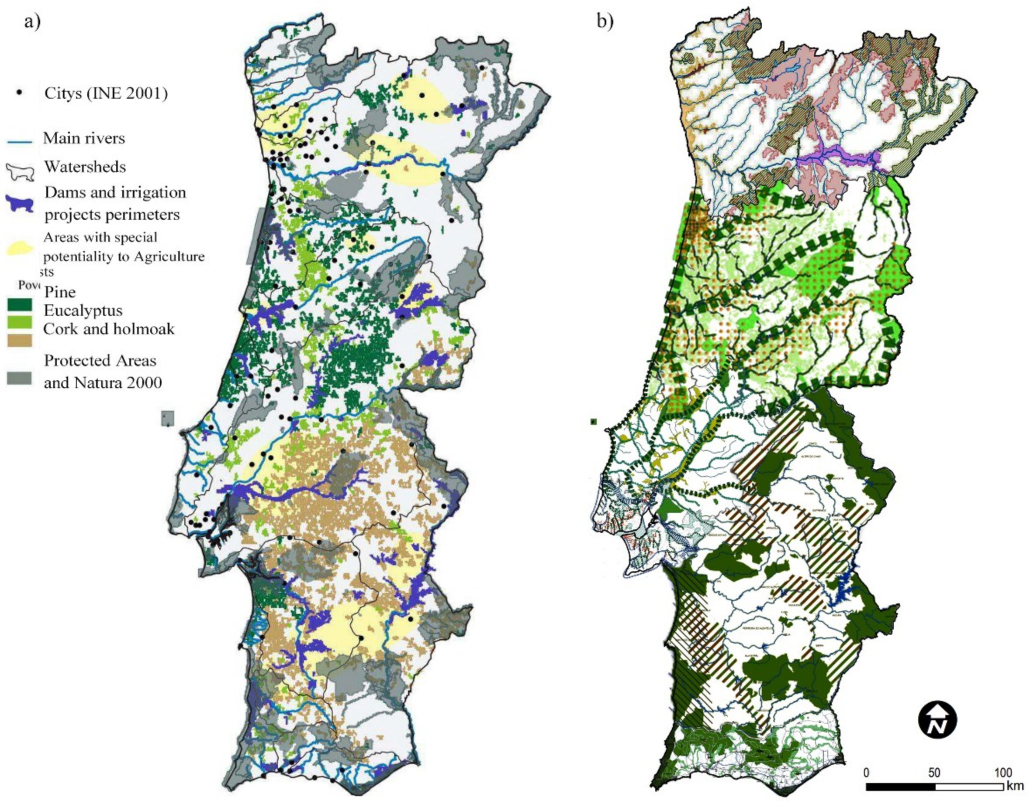

Figure A.26 a) Natural systems and agro-forestry in Portugal (DGOTDU, 2007) b) Ecological Networks in Regional Plans in Portugal (compilation of five the regional EN by the author)

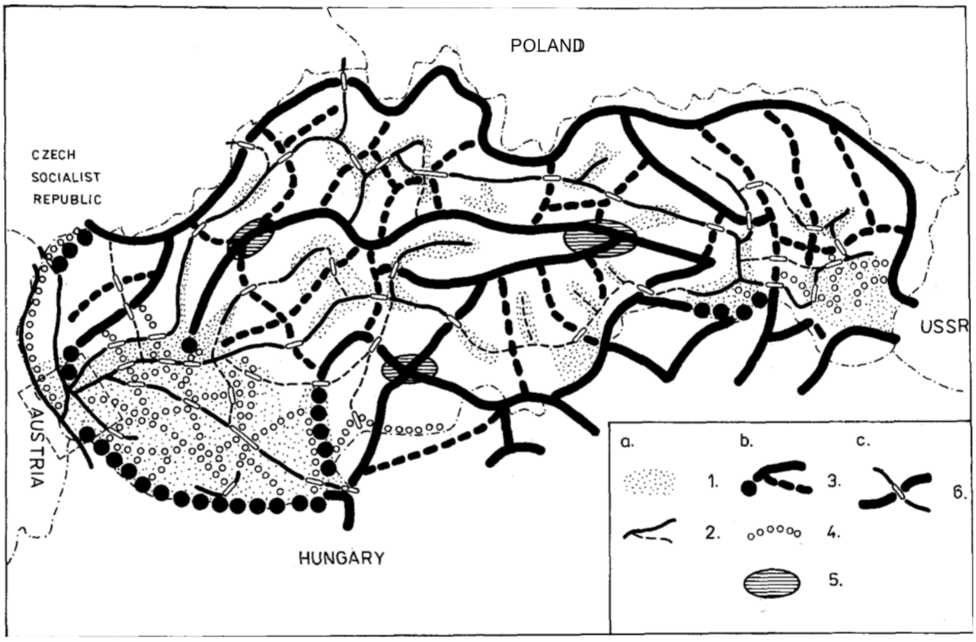

Fig. 2. Supraregional territorial system of ecological problems of the SSR.

a. Territorial system of ecological stress factors
   1. Regions of ecological problems
   2. Main and secondary corridors of stress factors – concurrently barriers of the linkage of the territorial system of ecological stability

b. Territorial system of ecological stability
   3. Main and secondary axes of ecologically more stable territorial blocks (belts)
   4. Axes of relatively isolated more stable territorial blocks (parts of blocks)
   5. Main ecological nodes

c. Encounters of the territorial systems
   6. Localisation of necessary connecting bridges for more stable territorial blocks. At the same time critical points of encounters of both systems.

Figure A.27 Territorial System of Ecological Stability (Miklós, 1989).

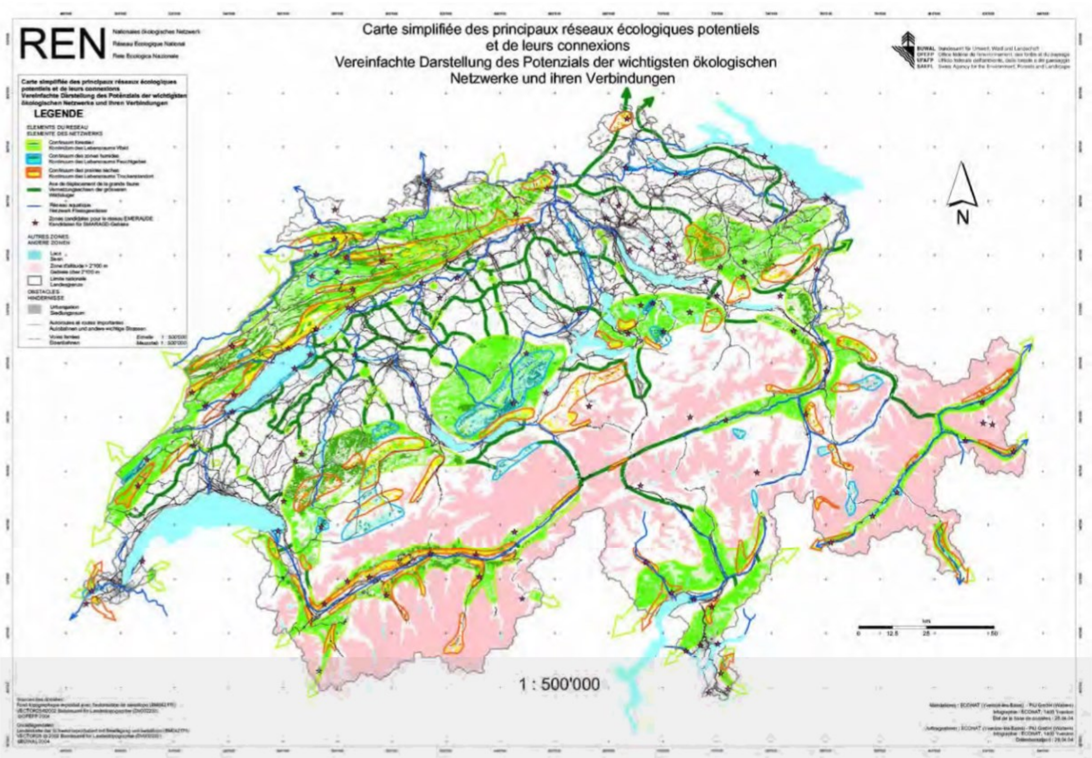

Figure A.28 Swiss résau écologique nacionale (Lebeau et al., 2004).

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2| IUCN (International Union for Conservation of Nature)

3| WWF (World Wildlife Fund) www.worldwildlife.org/ecoregions/

4| BISE (Biodiversity Information System for Europe) http://biodiversity.europa.eu/

5| European Green Belt http://www.europeangreenbelt.org/

6| OpenNESS project http://www.openness-project.eu/

American Association of Geographers http://www.aag.org/global_ecosystems

Agency for Nature Conservation and Landscape Protection Czech Republic

Baltic Sea Region Programme

BfN (the German Federal Agency for Nature Conservation)

BUND (Friends of the Earth Germany)

Croatia State Institute for Nature Protection

Danish Nature Agency

Danish Society for Nature Conservation http://eng.naturstyrelsen.dk

Dutch ministry of agriculture, nature and food quality https://www.government.nl/topics/nature-and-biodiversity/

Institute of Landscape Ecology, Slovak Academy of Sciences (ILE-SAS)

Macedonian Ecological Society

Ministry of Environment of the Republic of Lithuania http://www.glis.lt

Natural England http://www.gip-uk.org/

Green Infrastructure Valuation Toolkit greeninfrastructurenw.co.uk

APPENDIX B

B.1 Ecological Network and the Portuguese landscape planning tools

Table B.1 Relation between Ecological Network and the other Portuguese landscape planning tools at national, regional and municipal level (extended) in Portuguese.

Table B.2 The Ecological Networks at Portuguese regional planning level in Portuguese.

Table B.3 Relation between NEN1 componentes and the Portuguese legislative planning (in Portuguese).

Table B.4 Relation between NEN2 components and Portuguese legislative planning (cont) in Portuguese.

Appendix B

Table B.1 Relation between Ecological Network and the other Portuguese landscape planning tools at national, regional and municipal level (extended) in Portuguese.

<table>
<tr><th rowspan="3"></th><th colspan="9">NACIONAL</th><th colspan="2">REGIONAL</th><th colspan="4">MUNICIPAL – PMOT (DL nº 80/2015)</th></tr>
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(DL n.º 242/2015)</th><th colspan="3">SECTORIAIS</th><th colspan="3">PEOT</th><th>PROT</th><th>PROF</th><th colspan="2">PDM</th><th>PU</th><th>PP</th></tr>
<tr><th>PNA, PGBH, PEGA</th><th>ENGIZC</th><th>PSRN</th><th>POOC</th><th>POE</th><th>POAP</th><th></th><th></th><th>Solo Rústico</th><th>Solo Urbano</th><th></th><th></th></tr>
<tr><td rowspan="2">EE</td><td>Art.º 28
DLnº46/2009
Áreas de interesse nacional em termos ambientais</td><td rowspan="2">-</td><td rowspan="2">Determinação das condições de referência ou do máximo potencial ecológico específico do tipo de águas superficiais</td><td rowspan="2">Litoral, Orla e Zona Costeira</td><td rowspan="2"></td><td colspan="3" rowspan="2">Áreas fundamentais param a conservação da natureza e da biodiversidade</td><td rowspan="2">ERPVA</td><td rowspan="2">-</td><td colspan="2">EEM
Art 14.º DL nº46/2009
Art 10ºf) and 96ºc) DL nº 80/2015</td><td rowspan="2">Art.º 99.º
DL nº80/2015
b) EE</td><td rowspan="2">107º 4b)
DL nº80/2015
b) EE</td></tr>
<tr><td>Medidas prioritárias 1.2.5
Definir EE nos PROT e PMOT</td><td>DReg nº9/2009
Áreas da RFCN sujeitas a riscos Artº13 2.a) DReg nº11/2009
Compatibilidade com ERPVA</td><td>Art. 21.º
DReg nº11/2009
d) Espaços verdes</td></tr>
<tr><td>DPH</td><td rowspan="4">Sistemas naturais e agro-florestais</td><td>Áreas de continuidade</td><td>Águas e massas de água superficiais e subterrâneas</td><td></td><td></td><td>Art.º 21 e)
Lei n.º 58/2005
Ecossistemas Litorais
Art. 6º Port. n.º 767/96</td><td>Art.º 4º
DL nº 129/2008 de 21/7
Gestão ecossistemas estuarinos</td><td>Art.º 20 e) da Lei n.º 58/2005
Os valores naturais e paisagísticos a preservar</td><td rowspan="3">e) Art. 51º DL nº46/2009
Directrizes relativas às áreas de RAN, DPH, REN, e zonas de risco</td><td>Conservação do solo e protecção do regime hídrico
Áreas costeiras-Recreio, enquadramento e estética da paisagem</td><td colspan="4">Art. 12.º DL nº46/2009
Recursos e valores naturais
Parâmetros de ocupação e de utilização do solo adequados à salvaguarda e valorização dos recursos e valores naturais</td></tr>
<tr><td>RAN</td><td>Áreas de continuidade
Art.º 4 f) DL n.º 73/2009</td><td colspan="3" rowspan="2">Aplicam-se todas as servidões administrativas e restrições de utilidade pública
Princípios e directrizes que concretizam as orientações políticas relativas à protecção dos recursos e valores naturais</td><td colspan="3" rowspan="2">Aplicam-se todas as servidões administrativas e restrições de utilidade pública
Garantir a articulação com os IGT – PMOT
Usos preferenciais, condicionados e interditos</td><td>Arborização de áreas agrícolas marginais</td><td>Planta de condicionantes
Artº.11Cap. IV DL n.º 73/2009</td><td>x
Art.º 10
Cap. IV DL n.º 73/2009</td><td>x</td><td>x</td></tr>
<tr><td>REN</td><td>Áreas de continuidade
Art.º.3 3 DL n.º 166/2008</td><td>Conservação do solo e protecção</td><td>Alin 4 Art.º 9
DL166/2008
Planta de condicionantes
e constituem parte integrante das EEM</td><td>REN "bruta"
Planta de condicionante s - propostas de exclusão</td><td></td><td></td></tr>
<tr><td>SNAP</td><td>Áreas nucleares CNB</td><td>Áreas protegidas
(AP)</td><td></td><td>ZPE e SIC</td><td colspan="3">Áreas protegidas
(AP)</td><td>Áreas de Conservação</td><td>Art.15 DL nº 16/2009
Programa de gestão da biodiversidade</td><td>Art. 16.º DReg nº11/2009
Espaços Naturais</td><td colspan="3">PMOT podem ser objecto de Alteração:
e) As alterações aos POAP decorrentes de alterações dos limites da AP</td></tr>
</table>

Table B.2 The Ecological Networks at Portuguese regional planning level in Portuguese.

ERPVA		PROT N (CCDR N, 2009) RCM n.º 29/2006, de 23/3			PROT C (CCDR C, 2010) RCM n.º 31/2006, de 23/3			PROT OVT 09 (CCDR LVT, 2009) RCM n.º 64-A/2009, de 25/6		
		Subsistemas	**Componentes**	**Bases**	**Subsistemas**	**Componentes**	**Bases**	**Subsistemas**	**Componentes**	**Bases**
Terminologias		Unidades de Paisagem Unidades Territoriais			Unidades de Paisagem Áreas de “mais-valia” ambiental			Unidades Territoriais		
Áreas nucleares	**Áreas classificadas**	Áreas classificadas	RNAP RN 2000 Parque Arqueológico do Côa, Alto Douro Vinhateiro	RNAP Sítios Natura 2000 e ZPE’s Lista do Património Mundial	Áreas classificadas	RNAP; RN 2000 IBA Reservas biogenética CE	Áreas Classificadas	Estruturantes	Rede Nacional de Áreas Protegidas Rede Natura 2000	Áreas Classificadas
	Outras áreas sensíveis	-	-	-	Biótopos naturais de valor, não classificados	Povoamentos de folhosas autóctones Matos esclerolíticos Zonas húmidas (estuários, lagunas litorais, pauis, salinas e sapais) Sistemas dunares e arribas costeiras	COS 90 CLC 2000	Secundárias	Matos, matagais e as zonas húmidas mais significativas Áreas húmidas, baixas aluvionares, recursos hídricos subterrâneos	Padrões de ocupação do solo
Corredores Ecológicos	**Estruturantes Primários**	Estruturantes	Rede hidrográfica principal	Rede hidrográfica principal	Estruturantes	Rede Hidrográfica Principal Zona Costeira	Rede hidrográfica	Estruturantes Principais	Corredor vale do Rio Tejo Corredor vale do Rio Sorraia Corredor Litoral, Corredor Serrano	Rede hidrográfica principal Padrões de ocupação do solo
	Estruturantes Secundários	Terras altas (cota mínima 700m)	Sistemas de montanha Principais cabeceiras de linhas de água e zonas estratégicas de reserva de água	Hipsometria Declives	Secundários	Corredores Ecológicos dos PROF	PROFs Centro	Secundários	Linhas de água com maior importância (vales aluvionares e galerias ripícolas significativas)	
		Terras baixas (cota máxima <50m)	Principais áreas aluvião/solos agrícolas, Territórios de baixa altitude e orla costeira	Hipsometria Declives Aluviões					Eixos de continuidade de vegetação natural e seminatural; zonas declivosas e com afloramentos rochosos; bosquetes, matagais e matos mediterrânicos, e formações ripícolas	

Table B.2 The Ecological Networks at Portuguese regional planning level (cont.).

ERPVA		**PROT AML (CCDR LVT, 2010)** RCM n.º 92/2008, de 05/6			**PROT ALENT (CCDR Alentejo, 2010)** RCM n.º 53/2010, de 16/7			**PROT ALGARVE (CCDR 2007)** RCM n.º 102/2007, de 24/5		
		Subsistemas	**Componentes**	**Bases**	**Subsistemas**	**Componentes**	**Bases**	**Subsistemas**	**Componentes**	**Bases**
Terminologias		Rede Ecológica Metropolitana, Estrutura Verde Metropolitana Unidades Territoriais			Estrutura Ecológica			SistemaAmbiental, Estrutura Ecológica Urbana Unidades Ecológicas		
Áreas nucleares	**Áreas classificadas**	Estruturantes Primárias	RNAP Rede Natura 2000		Áreas nucleares	RNAP Sítios Natura 2000 e ZPEs	RNAP Rede Natura 2000	Áreas nucleares	RNAP Sítios Natura 2000 e ZPEs	RNAP Rede Natura 2000
	Outras áreas sensíveis	Estruturantes Secundárias	Áreas florestais, agrícolas, baixas aluvionares e áreas estuarinas	Padrões de ocupação do solo Conservação da natureza e biodiversidade	Áreas de conectividade ecológica predominanteme nte de montado	Matos naturais ou semi-naturais Sistemas florestais e silvo-pastoris (montados, florestas de quercíneas, habitats de pinhal manso em substrato arenoso)	-			
Corredores Ecológicos	**Estruturantes Primários**	Estruturantes Primários (CEP)	1.Litoral – Estuário do Tejo; 2.Vale do Tejo 3.Estuário do Tejo e Sado	Rede hidrográfica	Outras áreas de conectividade ecológica	Rede hidrográfica		Corredores Ecológicos (faixa mínima 500m)	Unidades ecológicas: Arribas; Azinhais + sobreirais + castinçais; Bosques ripícolas + cursos de água; Estuários + lagunas + sapais; Matagais + medronhais; Matos; Pinhais (Pinheiro Manso); Pomares de sequeiro; Prados + arvenses; Praias e sistemas dunares associados; Salinas	Rede Hidrográfica (base cartográfica não identificada) + COS 90
	Estruturantes Secundários	Estruturantes Secundários (CES)	Vales e linhas de água, permanentes ou temporárias, e respectivas margens, com maior importância regional	Rede hidrográfica	Litoral	Dunas e arribas costeiras Sapais e outras zonas húmidas	-			
Rede Complementar		Áreas vitais	Espaços livres de ocupação edificada integrados no interior de áreas urbanas compactas ou fragmentadas	Espaços Vazios sem Construção Carta Padrões de Ocupação do Solo		-			-	
		Corredores vitais	Ligações e espaços lineares parcialmente ou ainda livres de ocupação edificada	Rede Hidrográfica (linhas de água ou de drenagem natural, de menor nível hierárquico)		-			-	

Table B.3 Relation between NEN1 componentes and the Portuguese legislative planning (in Portuguese).

NÍVEL EE	COMPONENTES DA EE		REGIME JURÍDICO	FIGURA LEGAL	LEGISLAÇÃO
NEN1	Água	Linhas de água	DPH	«Massa de águas superficiais» uma massa distinta e significativa de águas superficiais, designadamente uma albufeira, um ribeiro, rio ou canal, um troço de ribeiro, rio ou canal, águas de transição ou uma faixa de águas costeiras	Art.º 4º Lei nº 58/2005
			REN Áreas relevantes para a sustentabilidade do ciclo hidrológico terrestre	2.1 — Cursos de água e respectivos leitos e margens – Para efeitos de delimitação a nível municipal consideram-se os leitos normais dos cursos de água que drenam bacias hidrográficas com um valor mínimo de 3,5 km2. São considerados também nesta tipologia as ínsuas, mouchões, lodeiros e areais, formados por deposição aluvial nos leitos dos cursos de água	Secção III c) do DL nº 239/2012
		Águas marinhas e costeiras	DPH	b) As águas superficiais situadas entre terra e uma linha cujos pontos se encontram a uma distância de 1 milha náutica, na direcção do mar, a partir do ponto mais próximo da linha de base a partir da qual é medida a delimitação das águas territoriais, estendendo-se, quando aplicável, até ao limite exterior das águas de transição;	Art.º 4º Lei nº 58/2005
				Oceanos e outros planos de água salgada. Inclui águas costeiras salobras separadas do mar por cordões arenosos ou lodosos, estuários, etc. (COS, 2007)	
		Águas transição (e embocaduras de rios)	DPH	c) Águas de superfície na proximidade da foz dos rios, que têm um carácter parcialmente salgado em resultado da proximidade de águas costeiras, mas que são significativamente influenciadas por cursos de água doce.	Art.º4º Lei nº 58/2005
			REN Áreas de protecção do litoral	1.10 — Águas de transição e respectivos leitos, margens e faixas de protecção	Secção III DL n.º 166/2008
		Águas interiores	DPH	*e*) Todas as águas superficiais lênticas ou lóticas (correntes) e todas as águas subterrâneas que se encontram do lado terrestre da linha de base a partir da qual são marcadas as águas territoriais;	Art.º4º Lei nº 58/2005
				Cursos de água e planos de água, naturais e artificiais, que incluem lagoas interiores naturais, charcas e reservatórios de barragens, de represas e açudes (COS, 2007)	
			REN Áreas relevantes para a sustentabilidade do ciclo hidrológico terrestre	2.2 — Lagoas e lagos e respectivos leitos, margens e faixas de protecção 2.3 — Albufeiras que contribuam para a conectividade e coerência ecológica da REN, bem como os respectivos leitos, margens e faixas de protecção	Secção III DL n.º 166/2008
		Zonas Húmidas	Convenção Ramsar Zonas Húmidas de Importância Internacional	"Áreas de sapal, paul, turfeira, ou água, sejam naturais ou artificiais, permanentes ou temporários, com água que está estagnada ou corrente, doce, salobra ou salgada, incluindo águas marinhas cuja profundidade na maré baixa não exceda seis metros", à qual se acrescenta, com a última revisão, "podem incluir zonas ribeirinhas ou costeiras a elas adjacentes, assim como ilhéus ou massas de água marinha com uma profundidade superior a seis metros em maré baixa, integradas dentro dos limites da zona húmida"	DLn.º 101/80,
	Sistema Húmido	Zonas contíguas às linhas de água	DPH	Leito – Terreno coberto pelas águas, quando não influenciadas por cheias extraordinárias, inundações ou tempestades, nele se incluindo os mouchões, lodeiros e areais neles formados por deposição aluvial, sendo o leito limitado pela linha da máxima preia-mar das águas vivas equinociais, no caso de águas sujeitas à influência das marés	LEI nº 54/2005 Lei nº 58/2005
				Margem – Faixa de terreno contíguo ou sobranceira à linha que limita o leito das águas com largura 50, 30 ou 10m	
				Zona inundável -	
				Zonas adjacentes –a zona contígua à margem que como tal seja classificada por um acto regulamentar por se encontrar ameaçada pelo mar ou pelas cheias	
			REN Prevenção de riscos naturais	2.1 — Cursos de água e respectivos leitos e margens	Secção III DL n.º 166/2008
				3.1 — Zonas adjacentes	
				3.3 — Zonas ameaçadas pelas cheias ou Zona inundável	Secção III c) do DL nº 239/2012
				3.2 — Zonas ameaçadas pelo mar	DL n.º 166/2008 de 22/8

Appendix B

NÍVEL EE	COMPONENTES DA EE		REGIME JURÍDICO	FIGURA LEGAL	LEGISLAÇÃO
NEN1	**Solo**	Solo de elevado e muito elevado Valor Ecológico	RAN	a) Solos A, B e Ch	Cap. II. Art.º 7 do DL n.º 73/2009 de 31/3
				b) As áreas com unidades de solos classificados como baixas aluvionares e coluviais	Art. º 8 Cap. III do DL n.º 73/2009 de 31/3
				Integração específica de solos: a) Tenham sido submetidas a importantes investimentos destinados a aumentar com carácter duradouro a capacidade produtiva dos solos ou a promover a sua sustentabilidade; b) O aproveitamento seja determinante para a viabilidade económica de explorações agrícolas existentes; c) Assumam interesse estratégico, pedogenético ou patrimonial	Art.º 9.º Cap. III do DL n.º 73/2009 de 31/3
	Litoral	Batimétrica dos 200 m (Plataforma continental)	Convenção das Nações Unidas sobre o Direito do Mar (CNUDM, 1982)	A plataforma continental de um Estado costeiro compreende o leito e o subsolo das áreas submarinas que se estendem além do seu mar territorial, em toda a extensão do prolongamento natural do seu território terrestre, até ao bordo exterior da margem continental ou até uma distância de 200 milhas marítimas das linhas de base a partir das quais se mede a largura do mar territorial, nos casos em que o bordo exterior da margem continental não atinja essa distância.	Art. 76.º da CNUDM Resolução n.º 60-B/97, de 14/87
		Batimétrica dos 30m	REN Áreas de protecção do litoral	1.1 — Faixa marítima de protecção costeira – é uma faixa ao longo de toda a costa marítima no sentido do oceano, correspondente à parte da zona nerítica com maior riqueza biológica, delimitada superiormente pela linha que limita o leito das águas do mar, ou pelo limite de jusante das águas de transição e inferiormente pela batimétrica dos 30 m. (Art.º4, Secção I DL n.º 239/2012)	Secção III DL n.º 166/2008 DL nº 239/2012 de 2 /11
		Ilha ou ilhéu		1.6 — Ilhéus e rochedos emersos no mar	
		Arribas		1.8 — Arribas e respectivas faixas de protecção	
		Zonas húmidas litorais		1.5 — Sapais	
		Areias de praia		1.2 — Praias	
		Areias Calhaus rolados e cascalheiras Dunas e areias de duna Depósitos de terraços marinhos		1.7 — Dunas costeiras e dunas fósseis	
		Estrutura litoral construída		1.3 — Barreiras detríticas (restingas, barreiras soldadas e ilhas-barreira) 1.4 — Tômbolos	
	Áreas declivosas	Áreas com declive> 25%	REN Áreas de prevenção de riscos naturais	3.4 — Áreas de elevado risco de erosão hídrica do solo – obtidas através da equação universal da perda de solo (USLE) 3.5 — Áreas de instabilidade de vertentes	Secção III d.2) DL nº 239/2012
	Vegetação	Vegetação natural e semi-natural com valor de conservação – nível Excelente e Muito elevado	Directiva Habitats		Dir. 92/43/CEE
	Conservação da Natureza	Rede Nacional de Áreas Protegidas (RNAP)	RFCN Áreas nucleares Conservação da Natureza e Biodiversidade (CNB)	Parque nacional, Parque natural, Reserva natural, Paisagem protegida, Monumento natural e Áreas Protegidas de estatuto privado (APP)	Decreto-Lei n.º 142/2008, de 24/7
		Rede Natura 2000		Rede Natura 2000, com informação das ZPE's e dos SIC's (Portaria n.º 829/2007, de 1/8)	DL n.º 49/2005, de 24/2
		IBAs		Áreas Importantes para Aves	Dir. 79/409/CEE
		Convenção de Ramsar		Convenção Ramsar para as Zonas Húmidas de Importância Internacional	DL n.º 101/80, de 9/10Alterado pelo Dec.n.º 34/91, de 30/4 e pelo Dec.do Governo n.º 33/84, de 10/7
		Reserva Biogenética do Conselho da Europa		Convenção de Berna (1979) - Área protegida com estatuto jurídico e caracteriza-se pela existência de um ou mais habitats, biocenoses ou ecossistemas únicos, raros e/ou ameaçados	DL n.º 316/89, de 22/9 alterado pelo DL n.º 196/90, de 18/6
		Reserva da Biosfera da UNESCO		Rede Mundial de Reserva da Biosfera (WNBR) deve conciliar três funções complementares: conservação, desenvolvimento e suporte logístico, através da definição de um modelo que integre áreas com graus de protecção diferentes, preconizando o seu desenvolvimento sustentável	The Man and the Biosphere Programme (1971)

Table B.4 Relation between NEN2 components and Portuguese legislative planning (cont) in Portuguese.

NÍVEL EE	COMPONENTES DA EE		REGIME JURÍDICO	FIGURA LEGAL	LEGISLAÇÃO
NEN2	**Cabeços em sistema húmido antigo**		-	--	
	Litoral	Áreas de Protecção do sistema litoral	REN Áreas de protecção do litoral	1.1 — Faixa marítima de protecção costeira 1.8 — Arribas e respectivas faixas de protecção 1.9 — Faixa terrestre de protecção costeira	Secção III d.2) DL nº 239/2012
	Geologia-Geomorfologia	Áreas de Máxima Infiltração	REN Áreas relevantes para a sustentabilidade do ciclo hidrológico terrestre	2.4 — Áreas estratégicas de protecção e recarga de aquíferos	Secção III d.2) DL nº 239/2012
			DPH Zona de infiltração máxima	Área em que, devido à natureza do solo e do substrato geológico e ainda às condições de morfologia do terreno, a infiltração das águas apresenta condições especialmente favoráveis, contribuindo assim para a alimentação dos lençóis freáticos	Art.38º Cap. III Lei nº 58/2005 de 29/12 (Lei da água)
	Vegetação	Vegetação natural e semi-natural com valor de conservação – nível Elevado, Moderado e Baixo	-	-	-
	Terras Altas	Hipsometria> 700 m		Interreg IVC project, 2010-2012. PADIMA - Policies Against Depopulation In Mountain Areas http://www.euromontana.org/en/projects.html 2006. 5ª Convenção Europeia da Montanha (Euromontana e ADRAT-Associação de Desenvolvimento Regional do Alto Tâmega) 1995. Secção de Municípios de Montanha da Associação Nacional de Municípios Portugueses (ANMP)	

B.2 Detailed NEN components combinations

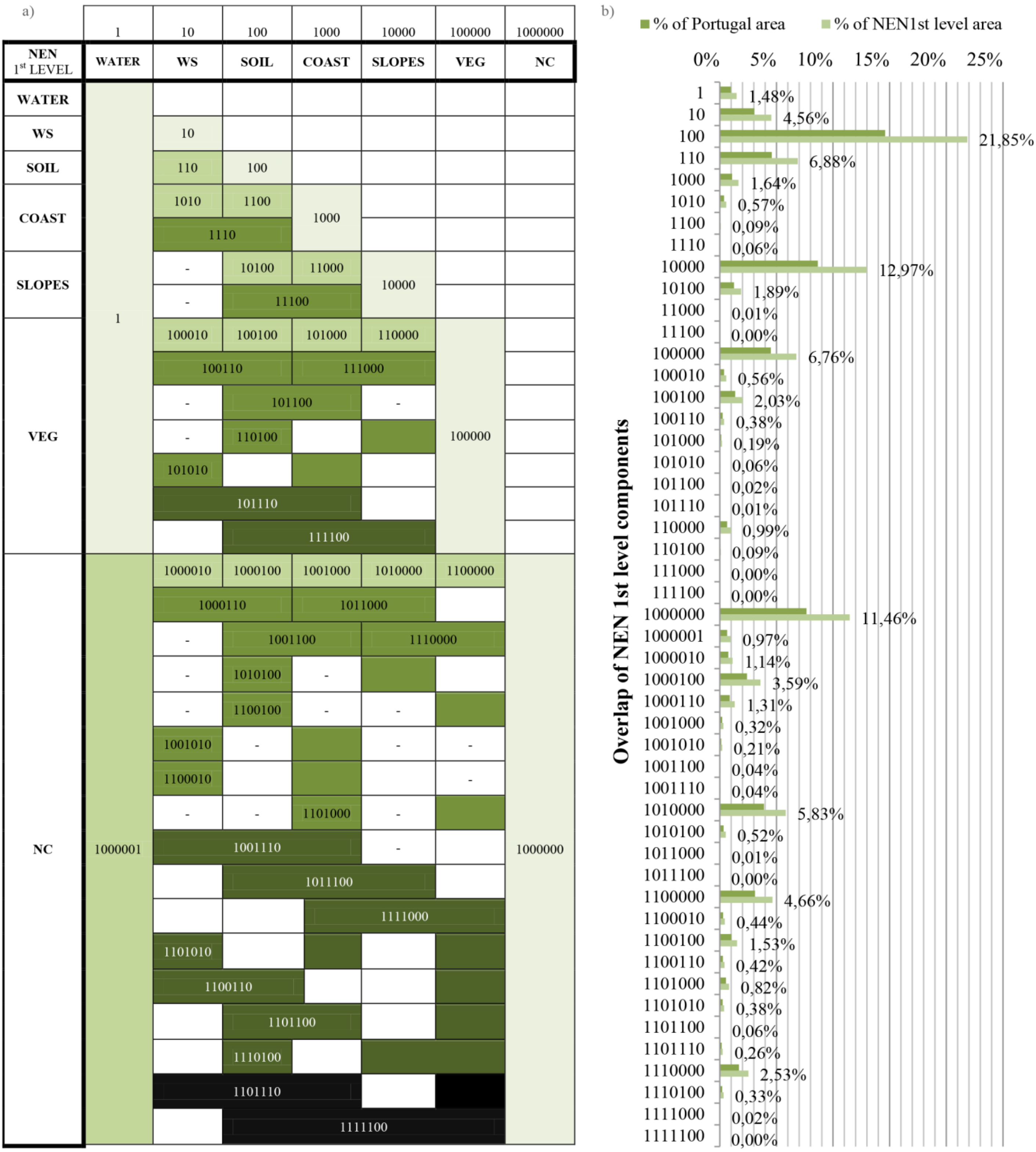

Figure B.1 a) Systematization matrix of NEN1 components; b) NEN1 components combinations.

a)

<table>
<tr><td></td><td>2</td><td>20</td><td>200</td><td>2000</td></tr>
<tr><td>NEN 2nd level</td><td>HWS</td><td>MInf</td><td>HLands</td><td>Veg2</td></tr>
<tr><td>HWS</td><td>2</td><td></td><td></td><td></td></tr>
<tr><td>MInf</td><td>22</td><td>20</td><td></td><td></td></tr>
<tr><td>HLands</td><td>-</td><td>220</td><td>200</td><td></td></tr>
<tr><td rowspan="3">Veg2</td><td>2002</td><td>2020</td><td>2200</td><td rowspan="3">2000</td></tr>
<tr><td colspan="2">2022</td><td>-</td></tr>
<tr><td>-</td><td colspan="2">2220</td></tr>
</table>

b)

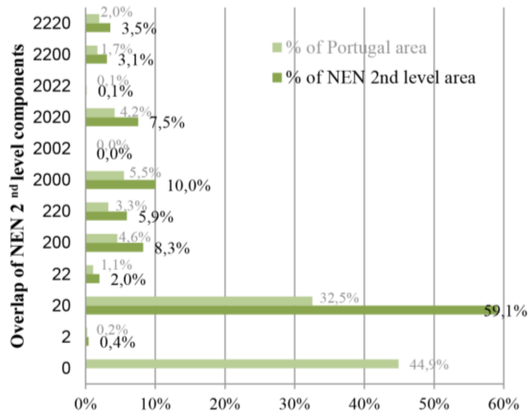

Figure B.2 a) Systematization matrix of NEN2 components; b) NEN2 components combinations.

B.3 Examples of regional and municipal Ecological networks

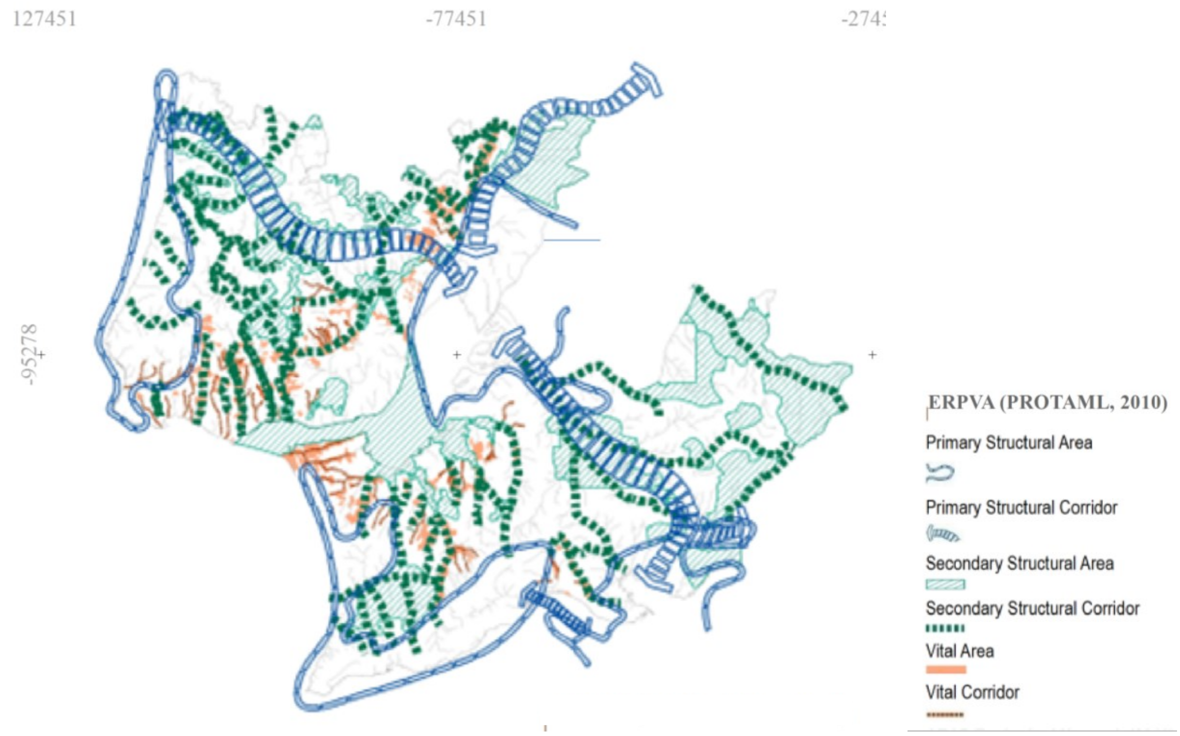

Figure B.3 Legal EN of Lisbon Metropolitan Area (ERPVA) (PROTAML, 2010).

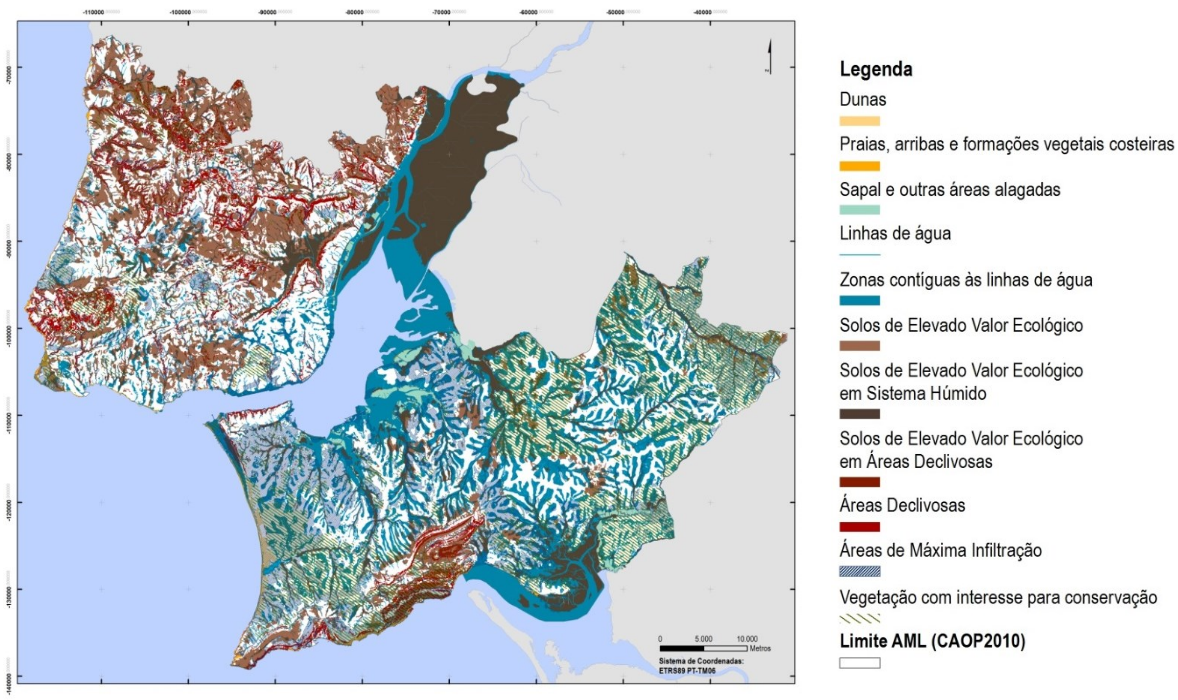

Figure B.4 Ecological network proposal for the Lisbon metropolitan area (Franco et al., 2013).

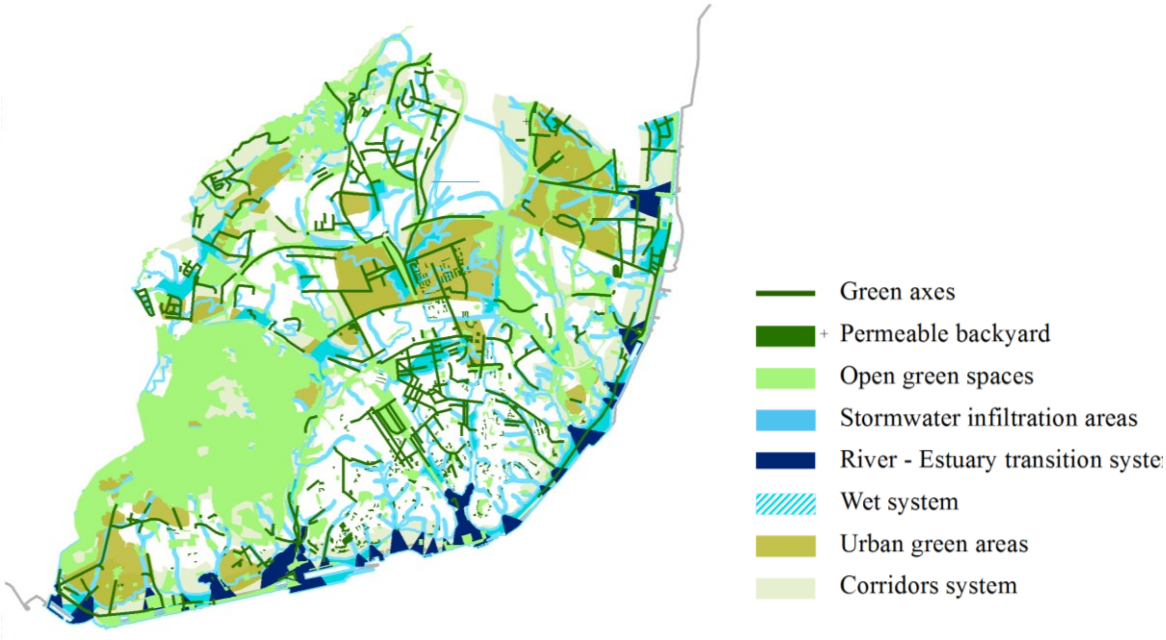

Figure B.5 Legal EN for Lisbon municipality (CML, 2012).

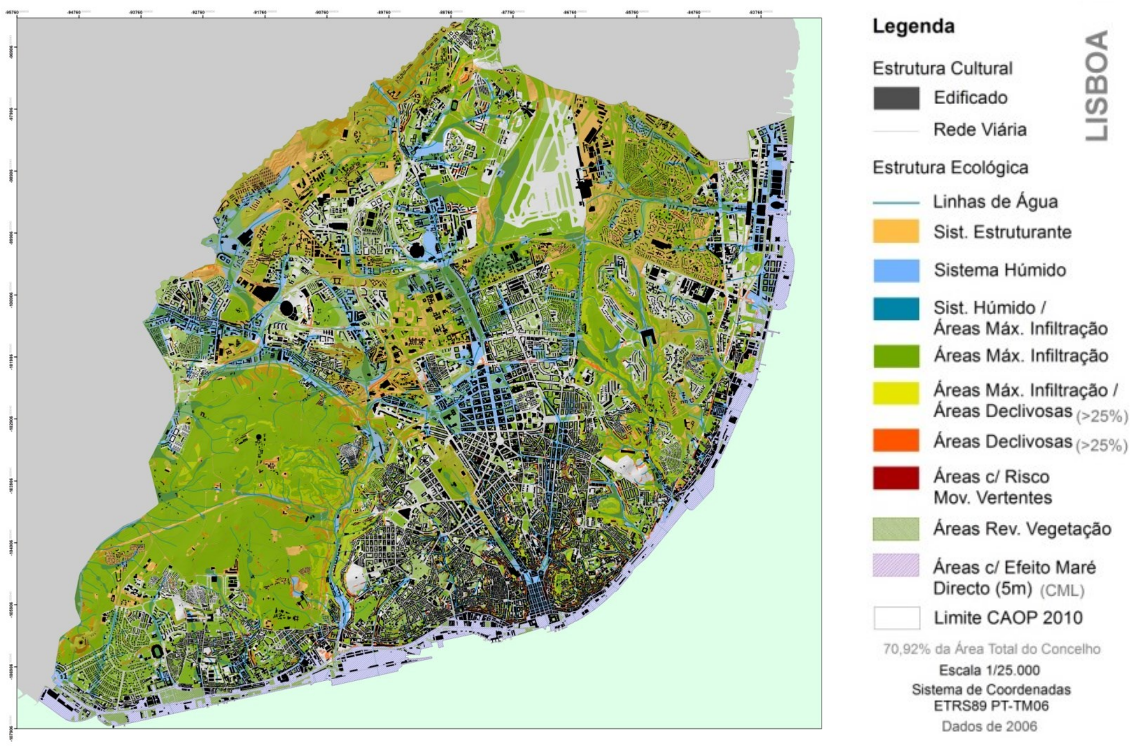

Figure B.6 Ecological network proposal for the Lisbon municipality (Ribeiro et al., 2013).

APPENDIX C

Land Morphology

Under the research project "National Ecological Network - a proposal of mapping and policies" (PTDC/AUR-URB/102578/2008), the Land Morphology was further developed to include a subclass of hilltops that comprehend Pleistocene fluvial terraces (hilltops in ancient wet system) (Figures C.1 and C.2). Such landforms correspond to the flattened areas that, border the wet system but are not situated in valley bottoms, since they are at a higher altitude even though the flood risk is real. The soils developed on them can no longer receive the addition of alluvial sediments and have a high organic matter content and usually have the groundwater at a deeper level (Cunha et al., 2013).

Figure C.1 Land Morphology map (Cunha et al., 2013).

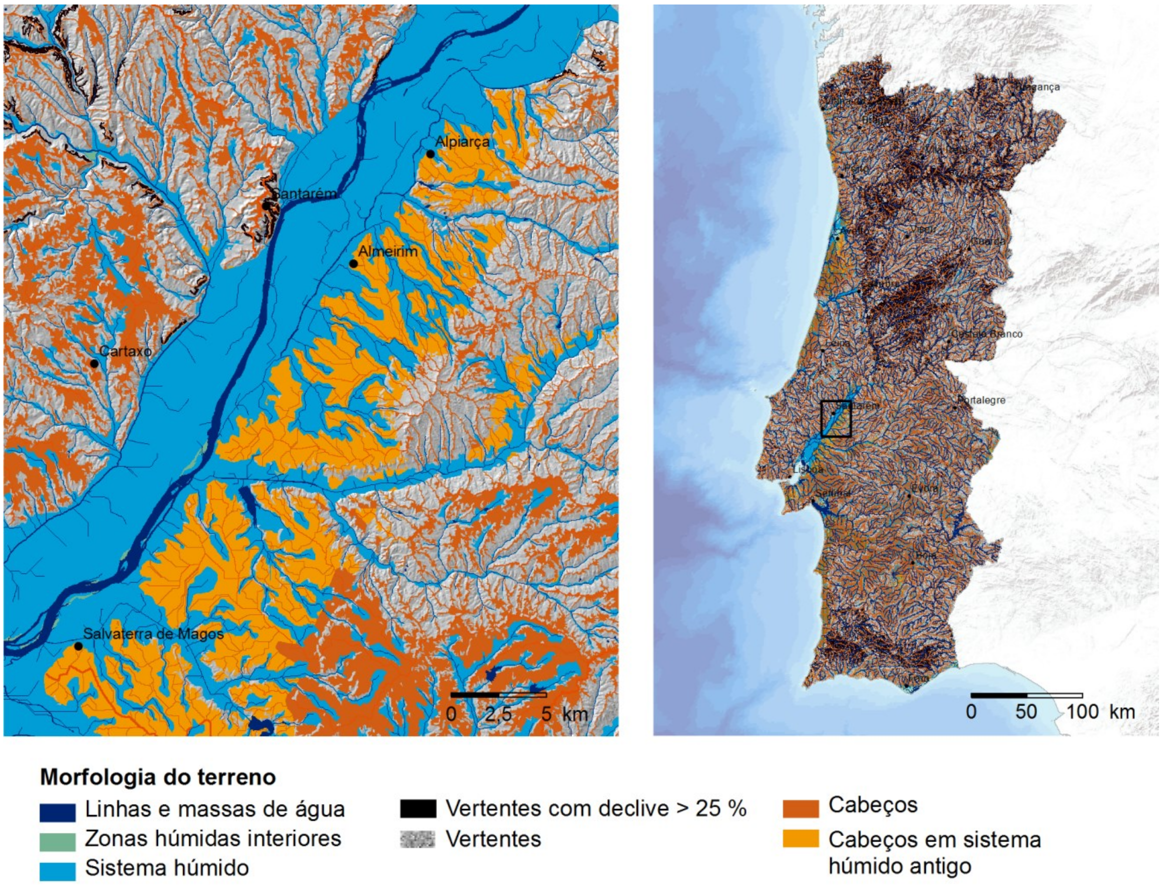

Figure C.2 Detail of the Land Morphology map with fluvial terraces in the left bank of Tagus River (Cunha et al., 2013).

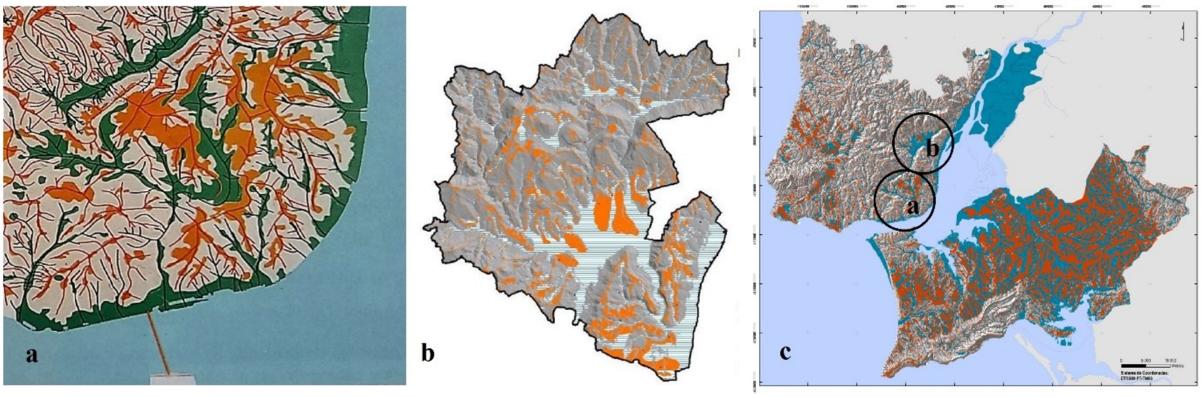

Figure C.3 Land morphology maps at different areas and scales a) Lisbon municipality (Magalhães et al. 1993); b) Loures municipality (Magalhães et al., 2002); c) Lisbon metropolitan area at regional scale (Franco et al., 2013). Green and blue represents valley bottoms, white or grey the hillslopes and orange the hilltops.

APPENDIX D

The Portuguese legislation on surface water resources

Table D.1 Summary of Portuguese legislation on surface water resources in Portuguese.

Legislação	Descrição	Delimitação
Regulamento dos Serviços Hidráulicos 1892	Documento 5534 Versão 1 Proíbe a construção nas Áreas inundáveis	c) O perímetro dos terrenos inundados pelas cheias ou permanentemente e a sua área respectiva;
Decreto n.º 5787/4I de 10/5/1919	Lei das Águas - Regulou o uso das águas	
Decreto-Lei n.º 468/71 de 5/11 (DL n.º 53/74 de 15/2 Altera DL n.º 468/71)	Lei dos Terrenos do Domínio Hídrico - Estabelece o regime jurídico dos terrenos incluídos no Domínio Público Hídrico (DPH) Classificação das zonas adjacentes e Definição das **zonas ameaçadas pelas cheias**	Art.º 14º do DL 468/71 - Zona Ameaçada pelas Cheias 1. Faixa de 100 metros em torno das linhas de água de 1ª e 2ª ordem 2. Áreas com declives inferiores a 2%, contíguas às linhas de água de 1ª e 2ª ordem, considerando-se que estas áreas potencialmente terão maior probabilidade de cheia. Uma vez que as áreas de declives inferiores a 2% também ocorrem em áreas de cabeceiras, partindo do princípio de que as áreas de cheia serão áreas de aluviões foi feita a intercepção destas duas áreas com vista a definir as potenciais áreas de cheias.
DL n.º 321/83	Regulamenta a REN que integra nos **Ecossistemas interiores**	c) Leitos normais dos cursos de água, zonas de galeria e faixas amortecedoras, além das suas margens naturais
DL nº 93/90	Regulamenta a REN que integra leitos dos cursos de água **e zonas ameaçadas pelas cheias**	
DL n.º 89/87	Demarcação de **zonas adjacentes** (sujeita a aprovação pelo INAG)	D. Reg. n.º 45/86, de 26/9 – classifica a zona adjacente à Ribeira da Laje. Portaria n.º 349/88, de 1/6 - zona adjacente a Ribeira das Vinhas. Portaria nº 105/89, de 15/2 – classifica como zona adjacente ao Rio Jamor a área delimitada como zona de ocupação edificada proibida e edificada condicionada. Portaria n.º 131/93, de 9/6 – delimita a zona adjacente a ribeira de Colares Portaria n.º 1053/93, de 19/10 – revoga a Portaria n.º 849/87 de 3/11, que classifica como zona adjacente ao Rio Zêzere toda a área inundável contígua às suas margens.
DL n.º 46/94 de 22/2	Estabelece o regime de licenciamento da utilização do DH, sob jurisdição INAG.	Regula o processo de planeamento de recursos hídricos e a elaboração e aprovação dos Planos de Bacia Hidrográfica
DL n.º 364/98, de 21/11	Estabelece a obrigatoriedade de elaboração por parte dos municípios com aglomerados urbanos atingidos por cheias num período de tempo que, pelo menos, incluísse o ano de 1967 e que ainda não se encontrassem abrangidos por zonas adjacentes, elaborarem **Cartas de Zonas Inundáveis** abrangendo os perímetros urbanos, visando a adopção de restrições à edificação face ao risco de cheia.	Áreas inundáveis - Delimitação das zonas potencialmente sujeitas a inundação, para o período de retorno de 100 anos ou no caso de se desconhecer este limite, numa faixa de 100 metros, para cada lado da linha da margem do curso de água.

Legislação	Descrição	Delimitação
Lei n.º 16/2003 de 4/6	3ª Alteração ao DL n.º 468/71, de 5/11 actualiza e unifica o regime jurídico dos terrenos DPH. Unificou o regime dos terrenos incluídos no DPH e a figura das zonas adjacentes, determinando a sujeição a restrições de utilidade pública dos terrenos considerados como ameaçados pelo mar ou pelas cheias.	Art.º 4º da Lei n.º 16/2003 de 4/6 – Zona Adjacente "1. Entende-se por zona adjacente toda a área contígua à margem que como tal seja classificada por decreto, por se encontrar ameaçada pelo mar ou pelas cheias. 2. As zonas adjacentes estendem-se desde o limite da margem até uma linha convencional definida, para cada caso, no decreto de classificação, nos termos e para os efeitos do presente diploma."
Lei n.º 54/2005 of 15/11 Lei da Titularidade dos Recursos Hídricos	Mantendo e desenvolvendo o regime jurídico aplicável às zonas adjacentes do DL 468/71. Estabelece que o Governo pode classificar como zona adjacente: as **zonas ameaçadas pelo mar** e as **zonas ameaçadas pelas cheias**, sujeitando-as a restrições de utilidade pública.	Art.º 24 º da LEI nº 54/2005 de 15/11 - Zona Adjacente "1. Área contígua à margem que como tal seja classificada, por se encontrar ameaçada pelo mar ou pelas cheias. 2. As zonas adjacentes estendem-se desde o limite da margem até uma linha convencional definida para cada caso no diploma de classificação, que corresponde à linha alcançada pela maior cheia, com período de retorno de cem anos ou à maior cheia conhecida, no caso de não existirem dados que permitam identificar a anterior.
Lei n.º 58/2005 of 29/12 Lei da Água	Estabelece as bases e o quadro institucional para a gestão sustentável das águas, transpondo para a ordem jurídica interna a Directiva n.º 2000/60/CE - DQA	Estabelece a obrigação de nos instrumentos de planeamento dos recursos hídricos e de gestão territorial serem demarcadas as **zonas inundáveis** ou ameaçadas pelas cheias incluindo-se as zonas ameaçadas pelo mar.
Decreto-Lei n.º 226-A/2007 de 31/5	Estabelece o regime jurídico da utilização dos recursos hídricos abrangendo as águas, respectivos leitos e margens, zonas adjacentes, zonas de infiltração máxima, zonas protegidas, em conformidade com a Lei da Água	
Decreto-Lei nº 391-A/2007 de 21/12 (Altera o DL 226-A/2007 Art.º 93º)	3- Até à entrada em funcionamento de cada ARH, a atribuição dos títulos de utilização relativos às barragens incluídas no Programa Nacional de Barragens de Elevado Potencial Hidroeléctrico é da competência do INAG.	
Decreto-Lei n.º 166/2008, de 22/8 Art.1 secção III - REN	REN criada pelo DL n.º 321/83 de 5/7 e cujo regime foi aprofundado pelo DL n.º 93/90 de 19/3	1 — As zonas adjacentes são áreas contíguas à margem que como tal seja classificada por um acto regulamentar, por se encontrar ameaçada pelo mar ou pelas cheias. 2 — A delimitação das zonas adjacentes é feita desde o limite da margem até uma linha convencional, definida caso a caso no diploma de classificação, que corresponde à linha alcançada pela maior cheia, com período de retorno de 100 anos, ou à maior cheia conhecida, no caso de não ser possível identificar a anterior.
Decreto-Lei n.º 180/2009 de 7/8	A aplicação dos regulamentos de harmonização da Directiva n.º 2007/2/CE, de 14/3 (INSPIRE) - SIG - no âmbito da elaboração das cartas de zonas inundáveis para áreas de risco e cartas de risco de inundações.	
Portaria 1284/2009 de 19/10	Estabelece o conteúdo dos Planos de Gestão de Bacia Hidrográfica	
Despacho n.º 6127/2010 de 7/4	Determina a elaboração do PNA 2010	

Legislação	Descrição	Delimitação
Decreto-Lei nº 115/2010 de 22/10	Transpõe para a ordem jurídica nacional a DIRECTIVA 2007/60/CE de 23/10 relativa a **avaliação e gestão dos riscos de inundações**	Delimitação das zonas ameaçadas pelas cheias:i) Em situações de risco, nomeadamente nos **perímetros urbanos**, nos aglomerados rurais e nas áreas de implantação de actividades económicas, devera ser sempre apoiada em estudo hidrológico referente a bacia hidrográfica e hidráulico a realizar para a o (s) troço (s) do curso (s) de água associados a esse risco; ii) Nas áreas onde não se perspective a existência de risco, a delimitação pode resultar apenas da representação da cota da maior cheia conhecida, determinada a partir de marcas de cheia, registos vários e dados cartográficos disponíveis, e/ou da aplicação de **critérios geomorfológicos (nomeadamente a existência de depósitos aluvionares modernos)**, pedológicos e topográficos.
Decreto-Lei n.º 130/2012 de 22/6	Procede à segunda alteração à Lei n.º 58/2005, de 29/12, que aprova a Lei da Água, transpondo a Directiva n.º 2000/60/CE, do Parlamento Europeu e do Conselho, de 23/10	Estabelece as bases e o quadro institucional para a gestão sustentável da água
Lei n.º44/2012 de 29/8	Sexta alteração ao Decreto-Lei n.º 226-A/2007, de 31/5	Estabelece o regime da utilização dos recursos hídricos
Decreto-Lei nº 239/2012 - **REN** Procede à primeira alteração ao Dec. Lei n.º 166/2008, de 22 de agosto	Delimitação da REN - Prevenção de riscos naturais 2.1 — Cursos de água e respectivos leitos e margens 3.1 — Zonas adjacentes 3.3 — Zonas ameaçadas pelas cheias ou Zona inundável 3.2 — Zonas ameaçadas pelo mar	Secção III c) do DL nº 239/2012 – **Zona Ameaçada pelas Cheias** "1 — Consideram-se zonas ameaçadas pelas cheias ou zonas inundáveis as áreas susceptíveis de inundação por transbordo de água do leito dos cursos de água devido à ocorrência de caudais elevados. 2 — A delimitação das zonas ameaçadas pelas cheias é efectuada através de modelação hidrológica e hidráulica que permita o cálculo das áreas inundáveis com período de retorno de 100 anos da observação de marcas ou registos de eventos históricos e de dados cartográficos e de critérios geomorfológicos, pedológicos e topográficos."
Lei nº 31/2014 de 30/05	Lei de Bases Gerais da Política Pública de Solos, de Ordenamento do Território e de Urbanismo	
Decreto-Lei nº 80/2015 de 14/05	Aprova a revisão do regime jurídico dos instrumentos de gestão territorial	Define o regime de coordenação de âmbito nacional, regional intermunicipal e municipais, o regime geral de uso do solo e o regime de elaboração, aprovação, execução e avaliação dos instrumentos de gestão territorial
Decreto-Lei n.º 242/2015, de 15/10	Procede à primeira alteração ao Decreto-Lei n.º 142/2008, de 24 de julho, que aprova o regime jurídico da conservação da natureza e da biodiversidade	
Lei n.º 31/2016, de 23 de Agosto	Terceira alteração à Lei n.º 54/2005, de 15 de novembro, que estabelece a titularidade dos recursos hídricos	