U.PORTO
FACULDADE DE CIÊNCIAS
UNIVERSIDADE DO PORTO

PhD

3.º CICLO
FCUP
2014

U.PORTO

Analysing hydrological services provided by forests to support spatial planning and land management

Cláudia Maria Carvalho dos Santos

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Analysing hydrological services provided by forests to support spatial planning and land management

Cláudia Maria Carvalho dos Santos
Tese de Doutoramento apresentada à
Faculdade de Ciências da Universidade do Porto
Biodiversidade, Genética e Evolução
2014

PhD

Analysing hydrological services provided by forests to support spatial planning and land management

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2014

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Água a correr na fonte,
Uma quimera líquida que sai
Das entranhas do monte
A saber ao mistério que lá vai…

Pura,
Branca, inodora e fria,
Cai numa pedra dura
E desfaz o mistério em melodia…

Miguel Torga, Diário II, 1948

Foreword

According to the number 7 of Article 6 from the Regulation of the Doctoral Program in Biodiversity, Genetics and Evolution (BIODIV), Faculdade de Ciências da Universidade do Porto (and in agreement with the Portuguese Law Decree nº 74/2006), this thesis integrates the articles listed below, written in collaboration with co-authors. The candidate hereby declares that she contributed to conceiving the ideas, compiling and producing the databases and analysing the data, and also declares that she led the writing of all Chapters.

List of papers:

Chapter 2 - Carvalho-Santos C., Hein L., Honrado J. (2014) Hydrological services and the role of forests: Conceptualization and indicator-based analysis with an illustration at a regional scale. Ecological Complexity. 20: 69-80. DOI: 10.1016/j.ecocom.2014.09.001

Chapter 3 - Carvalho-Santos C., Marcos B., Espinha Marques J., Alcaraz-Segura D., Hein L., Pradinho Honrado H. (2013) Evaluation of hydrological ecosystem services through remote sensing. In Alcaraz Segura D, Di Bella C M; Straschnoy J V (eds), Earth Observation of Ecosystem Services, CRC Press Taylors and Francis group, Boca Raton, pp. 219-249. ISBN 9781466505889.

Chapter 4 - Carvalho-Santos C., Nunes J.P., Monteiro A.T., Hein L, Honrado J. (under review) Simulating the effects of land cover and future climate conditions on the provision of hydrological services in a medium-sized watershed of Portugal.

Chapter 5 - Carvalho-Santos C., Silva A.R., Gonçalves J., Honrado J. (submitted) From hydrological services to a multifunctional watershed: trade-offs and synergies between biodiversity conservation and forest ecosystem services.

This thesis was supported by the Portuguese Science Foundation (FCT) through the PhD grant SFRH/BD/66260/2009

Este trabalho foi realizado com o apoio da Fundação para a Ciência e Tecnologia (FCT), através da bolsa de doutoramento com a referência: SFRH/BD/66260/2009 (QREN-POPH, tipologia 4.1)

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Acknowledgments

Our achievements would never be possible without the collaboration and interaction with the people that surround us. During the last four years and a half, many people took part of this PhD journey, which directly or indirectly contributed to my learning process and supported me in the good and bad moments.

First of all, I'm very grateful to my supervisor, João Honrado, for receiving me in his research group, encouraging me to explore and develop my ideas and supporting me in this PhD adventure.

I would like to thank Lars Hein for the co-supervision of this thesis, especially during the first two years where everything is a vague idea of what we want to develop further.

My sincere gratitude to Rik Leemans for having received me in ESA group, where during 2 years I was offered a desk, a computer, the inclusion in SENSE program, and the access to all facilities in Wageningen, including the opportunity to attend master classes. Many thanks also for the discussions and in particular for the special way of teaching.

A very special thanks to João Pedro Nunes, my current “boss”, to whom I owe all the learning process of SWAT model, and all the motivation to keep going the work in a field that was new and difficult in the beginning. Thanks for the more than 500 emails exchanged and the extensive chats in Skype. Thanks for all the patience, the contagious joy, the share of knowledge, and especially for giving me the opportunity to further continue in research after the PhD. It has been a pleasure working with you in Aveiro.

A big thanks to my work colleagues, both in Portugal (PRECOL-CIBIO) and in The Netherlands (ESA group), for helping in duties and questions about many issues, and for giving me the motivation for continuing with this research.

I started my PhD in ESA group (2010) and I would like to thank to all ESA members for the nice coffee breaks and lunch walks, and especially a big thank to Katalin, Alexander, Anne, Slava, Sander, Matthias and Roy for the “Monday meettings”.

Back to Portugal in 2012, I'm particularly grateful to those who directly have worked with me and are sharing the publications of this thesis. An enormous thank to Antonio Monteiro, for pushing me up when I was unmotivated, and for helping me with the climate change studies. Ana Rita Silva, my daily fellow, nowadays via Skype, thanks a million for hearing me and helping me with the biodiversity maps. Thanks also for your friendship - I miss a lot our lunch walks! Bruno Marcos, thanks for the nice discussions about remote sensing and satellites, but especially, thanks for the “piadas à Bruno”! And João Gonçalves, for the extraordinary conversations exchanged and all the input given, even being so busy.

There are also other important colleagues that I have to mention: Cristiana Vieira for the very nice period spent together in The Netherlands, and the helpful advices in the academic and not so academic matters. Paulo Alves, the "alive encyclopedia" for the all the knowledge transferred during our nice conversations, and especially for all the joy in our lunch walks. I will never forget the utilities of a young eucalypt! Cláudia Soares for being an "old sister". Anabela Amado for showing the natural things. To all people in Porto lab, especially the "Criptodivas" Joana, Helena e Cristiana and the "Criptodivas bebés" Paula, Cristiana e Cláudia for being my fellows in Porto room when I was finishing this thesis. To all people in Vairão lab: Ângela, Joana, Sofia, Emilio and Zé António for all the support. To Vânia Santos for being my first co-oriented student. To Laura Moreno for the very nice moments spent at the time of your Erasmus Mundus in Porto.

And a big thank to all people from "erosivos" - Dao Aveiro for received me during the days when I was trying to solve the problems in SWAT during the PhD, and now for being my fellows, especially Patricia for the long talks in the train.

I would like to express my gratitude to Jorge Espinha for contributing to the book chapter, part of this thesis, and for the nice talks exchanged and the nice way of teaching.

To all my friends in Portugal, especially my cousins Catarina e Angelo for being always present. A big thank to all of my friends in The Netherlands, many of them already spread around the world. Thanks for all the joy, the share of experiences, the opportunity of knowing more about the world.

Also important "things" should be acknowledged, such as Sublime FM radio, former Arrow Jazz FM from The Netherlands, for entertain me along this PhD, now via Internet connection.

And to my cat for amusing me when I was frustrated!

Finally, to my family, to whom I owe everything I am, my profound gratitude for accompanying me.

And to André, for had walking with me through all the steps of this journey. Eternal gratitude for being on my side.

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Resumo

A água é um recurso vital para todos os organismos vivos da Terra. Os seres humanos dependem dos ecossistemas para a prestação de serviços hidrológicos, tais como o abastecimento de água e a mitigação de danos causados pela água, que são essenciais para o seu bem-estar. No entanto, as preocupações com os problemas relacionados com a água têm vindo a aumentar nas últimas décadas, com especial ênfase para a escassez de água, a sua qualidade e os desastres causados por ela, incluindo as questões relacionadas com as alterações climáticas. Isso tem suscitado o interesse na gestão sustentável dos ecossistemas, em particular das florestas, para a prestação de serviços hidrológicos, tendo em conta o reconhecimento dos processos que suportam essa provisão. Por conseguinte, os serviços hidrológicos devem ser adequadamente conceptualizados, quantificados, mapeados e monitorizados. O principal objetivo de investigação desta tese foi desenvolver quadros teóricos e analíticos para avaliar os serviços dos ecossistemas hidrológicos prestados pelas florestas, apoiando assim as opções para o planeamento e gestão do território. Embora o foco geral desta tese seja o desenvolvimento de abordagens metodológicas, os resultados dessas novas abordagens tem também um potencial para o apoio à tomada de decisão sobre a gestão de bacias hidrográficas. Este potencial foi ilustrado para a bacia hidrográfica do rio Vez, no Noroeste de Portugal, onde a precipitação é alta, embora desigualmente distribuída ao longo do ano, com potencial para a ocorrência de episódios extremos relacionados com a água.

A pesquisa desenvolvida nesta tese é apresentada ao longo de seis etapas sucessivas. Primeiro foi apresentado o estado da arte sobre os diferentes níveis de análise dos serviços hidrológicos, *capítulo 1*. Em segundo lugar, no *capítulo 2*, foi elaborado um quadro conceptual para a prestação de serviços hidrológicos com base nas relações entre a água e as florestas, e no contexto da análise de sistemas sócio-ecológicos. Este quadro conceptual foi ilustrado para o abastecimento de água e os serviços de controle da erosão do solo e aplicado a uma escala regional, o Norte de Portugal. Os resultados mostram que o quadro conceptual proposto é uma ferramenta útil de apoio ao ordenamento do território e à gestão florestal, adequando a prestação de serviços hidrológicos com as condições biofísicas e sociais de cada região. A aplicação do quadro sugere que a combinação espacialmente explícita de indicadores relacionados com a propriedade do sistema, as funções, o serviço e o benefício pode ser uma forma eficaz de análise e gestão da oferta e da procura por serviços hidrológicos.

Posteriormente, no capítulo 3 é apresentada uma visão geral dos produtos de satélite que podem ser usados para avaliar e monitorizar a prestação de serviços hidrológicos, com base nos diferentes compartimentos de água existentes na Terra (atmosfera, criosfera, água de superfície, solo, aquífero e vegetação). A avaliação dos serviços de abastecimento de água e de mitigação de danos causados por ela pode beneficiar fortemente do uso de produtos de satélites, contribuindo para uma melhor compreensão dos processos e funções que estão na base da sua provisão, com elevada cobertura espacial e resolução temporal.

Como a ilustração dos serviços hidrológicos apresentados no capítulo 2 foi baseada em modelação estática, foi testada a aplicação de uma estrutura de modelação dinâmica para avaliar o papel das florestas na prestação de serviços hidrológicos. Assim, no *capítulo 4*, o modelo hidrológico SWAT (Ferramenta de Avaliação de Água e Solo) foi aplicado na bacia hidrográfica do Vez para analisar a prestação de serviços hidrológicos em cenários de alteração do uso/cobertura do solo e as condições climáticas futuras. Os resultados das simulações relativamente aos cenários de cobertura do solo revelaram que a opção por um determinado cenário não comprometeria a prestação global dos serviços hidrológicos. No entanto, cada cenário pode ser adoptado para

maximizar a prestação de um determinado serviço, por exemplo florestas de carvalhos naturais podem ser promovidas para melhorar a libertação gradual de água no rio. O estudo mostra ainda que a alteração climática pode afetar a prestação dos serviços hidrológicos de duas maneiras, reduzindo os caudais na estação seca e aumentando os riscos de picos de caudal passiveis de criar inundações durante os meses de chuva. Os efeitos combinados de clima e alteração da cobertura de solo podem compensar os picos de caudal durante o inverno, mas agravar os baixos caudais de verão na presença de florestas. A erosão do solo e a concentração de nitratos no rio aumentarão em condições climáticas futuras, podendo ser agravadas no cenário de uso do solo agrícola. Estes resultados reforçam a necessidade de se considerar não só o clima, como também os impactos da mudança de uso do solo em opções de gestão que visam uma melhor adaptação às novas condições de provisão dos serviços relacionados com a água à escala de bacias hidrográficas.

Com base nos resultados das simulações do SWAT desenvolvidas no capítulo anterior, no *capítulo 5* foi desenvolvida uma avaliação espacial dos serviços hidrológicos, da produção de biomassa e do armazenamento de carbono, juntamente com a valoração da conservação da biodiversidade para analisar os conflitos e sinergias entre eles. Os resultados mostraram que o desempenho para o fornecimento da água (quantidade e sazonalidade) é melhor nos cenários de arbustos e de carvalhos, na sub-bacia de alta montanha. Enquanto o cenário de eucalipto e pinheiro tem maior desempenho para a prestação da regulação de picos de cheia e controle de erosão, especialmente na baixa montanha. Este último service é também favorável no cenário arbustivo. O melhor cenário para a conservação da biodiversidade é o de carvalho.

Finalmente no *capítulo 6* foram discutidas as contribuições metodológicas, os principais resultados e sua relevância para a gestão de políticas gestão dos usos do solo. A análise de serviços hidrológicos prestados pelas florestas é um tema que combina os princípios e métodos da eco-hidrologia com conceitos e métodos da ciência dos serviços de ecossistemas. As dimensões de análise abrangem não só a aquisição e aplicação dos fundamentos conceptuais de ambas as ciências, mas também uma descrição de formas de avaliação e monitorização para a prestação de serviços hidrológicos. Para além disso, deve também abranger o uso de ferramentas de modelação para ser capaz de entender e prever os processos hidrológicos e suas ligações com as funções ecológicas dos ecossistemas. As principais contribuições desta investigação foram: (1) o desenvolvimento de um quadro conceptual para a análise dos serviços hidrológicos prestados pelas florestas; (2) uma revisão exaustiva das muitas vantagens que a detecção remota oferece para a avaliação, gestão e monitorização de serviços hidrológicos; e (3) a aplicação do modelo SWAT a uma bacia de média dimensão para avaliar as consequências de diferentes opções de uso/cobertura do solo, bem como condições climáticas futuras, na prestação de serviços hidrológicos. Em conclusão, para uma correta avaliação dos processos hidrológicos que levam à prestação de serviços hidrológicos, o uso de modelos hidrológicos é uma abordagem eficaz, especialmente em associação com produtos de satélite para prever e monitorizar a condição das funções hidrológicas dos ecossistemas e paisagens.

Palavras-chave: Alterações Climáticas; Bacia Hidrográfica do Vez; Conservação da Biodiversidade; Florestas; Indicadores; Ordenamento do território; Produtos de satellite; Quadro conceptual; Serviços hidrológicos; SWAT .

Abstract

Water is a vital resource for all living organisms on Earth. Humans rely on ecosystems for the provision of hydrological services, namely water supply and water damage mitigation, essential for their well-being. However, concerns over the water problems have been increasing in the last decades, with special emphasis for water scarcity, quality and disasters, including issues related to climate change. This has been raising interest in the sustainable management of ecosystems, in particular of forests, for the provision of hydrological services, taking into account the recognition of the processes behind that provision. As a result, hydrological services should therefore be adequately conceptualized, quantified, mapped and monitored. The main objective of the research underlying this thesis was to develop theoretical and analytical frameworks to assess hydrological ecosystem services provided by forests, thereby supporting options for spatial planning and land management. Although the general focus of this thesis is on the development of methodological approaches, the outcomes from those novel approaches are expected to have a potential to support decision-making on the watershed management and governance. This potential was illustrated for the Vez watershed, in northwest Portugal, where precipitation is high, although unevenly distributed throughout the year, with possible occurrence of water extreme episodes.

The research developed for this thesis was addressed throughout six successive steps. First the current state of knowledge on the different levels of analysis of hydrological services, *chapter 1*, was presented. Secondly, in *chapter 2,* a conceptual framework for the provision of hydrological services based on the relations between water and forests was elaborated, in the context of social-ecological system analysis. This conceptual framework was illustrated for the water supply and soil erosion control services, applied at a regional scale for northern Portugal. Results show that the proposed conceptual framework is a useful tool to support land planning and forest management, adapting the provision of hydrological services to the regional biophysical and social conditions. The application of the framework across a heterogeneous region suggested that a spatially explicit combination of system property, function, service and benefit indicators can be an effective way of analysing and managing the supply and demand of hydrological services.

Subsequently, in *chapter 3*, an overview of the satellite products that can be used to evaluate and monitor the provision of hydrological services, based on the different water compartments on Earth (atmosphere, cryosphere, surface water, soil, ground and vegetation) was presented. The assessment of water supply and water damage mitigation services can strongly benefit from the use of satellite-based products, contributing to improve the understanding of the processes and functions behind their provision, on a spatially explicit and near-real time basis.

As the illustration of the hydrological services presented in *chapter 2* was based on a static modelling approach, the application of a dynamical modelling structure to evaluate the role of forests on hydrological services provision was then tested. Therefore, in *chapter 4*, the SWAT (Soil and Water Assessment Tool) hydrological model was applied in the Vez watershed to analyse the provision of hydrological services under scenarios of land use/cover change and future climate conditions. Results for the simulations under land cover scenarios revealed that the option for one particular scenario would not compromise the overall provision of hydrological services. However, each scenario may be adopted to improve the provision of a given service, for instance natural oak forests can be promoted to improve the gradual release of water into the river network. The study showed that climate change could affect the provision of hydrological services in two ways, by reducing dry season flows and by increasing flood risks during wet months. Combined effects of climate and land use change can offset peak flows during winter and reduce low flows in summer in the presence of forests. Soil erosion and

nitrates concentration in the river will increase under future climate conditions and could be aggravated in the agricultural land use scenario. These results emphasise the need to consider both climate and land use/cover impacts in management options aimed to improve adaptation to changed conditions in the water services at the watershed scale.

Based on the outputs from SWAT simulations developed in the previous chapter, in *chapter 5* a spatial assessment of the hydrological services, biomass production and carbon storage provision, together with the biodiversity conservation value was developed to analyse trade-offs and synergies to support land planning and management at the watershed scale. Results showed that the performance for the provision of water quantity and timing is better under the shrubland and oak scenarios, in the high mountain sub-basin. While the eucalyptus/pine forest scenario has higher performance for the provision of flood regulation and erosion control, especially in the low mountain. Erosion control is also favoured under the shurbland scenario. The scenario with less trade-offs with biodiversity conservation is the oak.

The methodological contributions, the main findings and their relevance for land management and policies were finally discussed in *chapter 6*. Analysing hydrological services provided by forests is a topic that combines principles and methods of eco-hydrology with concepts and methods from the novel ecosystem services science. The dimensions of the analysis encompass the acquisition and application of the conceptual foundations from both sciences, as well as a description of different ways for evaluating and monitoring the hydrological services provision. Moreover, it should also encompass the use of modelling tools to be able to understand (and predict) hydrological processes and their links to the ecological functions of ecosystems. The main contributions of this research were: (1) the development of a conceptual framework for the analysis of hydrological services provided by forests; (2) an exhaustive review of the many advantages that Earth observation offers for the evaluation, management and monitoring of hydrological services; and (3) the application of the SWAT model to a medium-sized watershed for the evaluation of the consequences of both land use/cover options and future climate conditions on the hydrological services provision. In conclusion, for a correct evaluation of the hydrological processes that lead to hydrological services provision, the use of daily-runoff models is an effective tool, especially in association with the powerful satellite products, to predict and monitor the condition of water functions in dynamic ecosystems and landscapes.

Keywords: Biodiversity conservation; Climate change; Conceptual framework; Forests; Hydrological services; Indicators; Land management; Satellite products; SWAT; Vez Watershed.

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List of abbreviations

ARIES - Artificial Intelligence for Ecosystem Services

CBD – Convention on Biological Diversity

CICES – Common International Classification of Ecosystem Services

CMIP5 – Coupled Model Intercomparison Project Phase 5 (IPCC)

DPSIR – Drivers Pressures States Impacts Responses

ESA – European Space Agency

ESb – Ecosystem Services beneficiaries

ESp – Ecosystem Services providers

ET – Evapotranspiration

EU – European Union

FAO – Agriculture Organization of the United Nations

FESP – Framework for Ecosystem Service Provision

GCM – General Circulation Models

GEO – Geostationary Orbit

GIS – Geographical Information System

GNSS – Global Navigation Satellite Systems

ha - hectare

HRU – Hydrological response unit (SWAT)

IAHS– International Association of Hydrological Sciences

InVEST – Integrated Tool to Value Ecosystem Services

IPBES – International science-policy Platform on Biodiversity and Ecosystem Services

IPCC– Intergovernmental Panel on Climate Change

IPMA – Portuguese Institute of the Sea and Atmosphere

IR – Infrared Radiation

LAI – Leaf Area Index

LEO – Low Earth Orbits

LiDAR – Light Detection and Ranging

MA – Millennium Ecosystem Assessment

MODIS – Moderate Resolution Imaging Spectroradiometer

MR – Microwave radiation

MUSLE – Modified Universal Soil Loss Equation (SWAT)

NASA – National Aeronautics and Space Administration

NGO– Non-governmental organizations

NIR – Near-Infrared Radiances

NOAA – National Oceanic and Atmospheric Administration

NPP – Net Primary Productivity

NSE – Nash-Sutcliffe efficiency

PBIAS – Per cent bias

PET – Potential Evapotranspiration

POES – Polar Orbiting Platforms

PR – Precipitation Radar

R^2 – Coefficient of determination

RADAR – Radio Detection and Ranging

RCM – Regional Climate Models

RCP – Representative Concentration Pathways

RUSLE – Revised Universal Soil Loss Equation

SNIRH – National System for Water Resources Information

SWAT – Soil and Water Assessment Tool

SWE – Snow Water Equivalent

TEEB – The Economics of Ecosystems and Biodiversity

TRMM – Tropical Rainfall Measuring Mission

VIS – Visible Radiation

yr – year

The abbreviations related to the satellite products were not described here, as they are described when mentioned in chapter 3.

Chapter 1

Introduction

"Water is the elixir of life on Planet Earth,
equally fundamental for humans as for ecosystems."

(Falkenmark & Rockstrom, 2004)

1.1. Ecosystem services, biodiversity and forests

Nature provides us with goods (such as timber), and services (such as regulation of water flow and quality), which together have been commonly called “ecosystem services” (de Groot, 1992; Daily, 1997) and more recently, eco-services (Costanza et al., 2014). Pressures such as land-use change, overexploitation, pollution and climate change are causing impacts on ecosystem services provision (MA, 2005; Rounsevell et al., 2010). From the awareness of the importance of those services for human well-being, responses based on spatial planning and land management, such as afforestation actions can be developed to improve ecosystem services delivery (Carpenter et al., 2009; EASAC, 2009).

The Millennium Ecosystem Assessment (MA), was the first international political and scientific effort leaded by the United Nations to assess the consequences of ecosystem change for human well-being (MA, 2003). According to the MA classification there are four categories of ecosystem services: provisioning (e.g. food, timber), regulating (e.g. carbon sequestration, water regulation), cultural (e.g. recreation, inspiration) and supporting services (e.g. soil formation, nutrient cycle) (MA, 2003). The first three categories have a direct impact on human well-being, while the latter gathers the essential processes that support the services in the first three categories, and so it is often not considered for economic assessments (Johnston & Russell, 2011). Several typologies for ecosystem services have emerged since the MA (de Groot et al., 2002; Wallace, 2007; de Groot et al., 2010b), also associated to global initiatives such as TEEB (The Economics of Ecosystems and Biodiversity), which draws attention for the economic costs of biodiversity loss and ecosystem degradation (de Groot et al., 2010a). More recently, CICES (Common International Classification of Ecosystem Services), a new classification system for ecosystem services developed by the European Environment Agency, structures the provisioning, regulating and cultural services by class, avoiding double-counting for economic studies (Haines-Young & Potschin, 2012).

Biodiversity, as part of ecosystems, has an important role in the provision of goods and services for human well-being (MA, 2003; Balvanera et al., 2006; Elmqvist et al., 2009) (Figure 1.1). Furthermore, it is accepted that changes in biodiversity may influence the supply of ecosystem services, as well as many aspects of ecosystem stability, functioning and sustainability (Costanza et al., 2007; Egoh et al., 2010; Mace et al., 2011; Perrings et al., 2011). In fact, some aspects of biodiversity are even considered as ecosystem services themselves, such as the habitat service (Hein et al., 2006), gene pool protection, biological regulation against pest(de Groot et al., 2010b), pollination and seed dispersal (MA, 2003). Biodiversity conservation is also considered as a service considering the cultural goods and amenities that humans can achieve from the existence of biodiversity and nature (Hein, 2010; Mace *et al.*, 2012). On the other hand, biodiversity conservation can be considered an important asset subject of trade-off analysis with ecosystem services provision (Nelson et al., 2009). Chapter 5 from this thesis deals with this dimension of biodiversity.

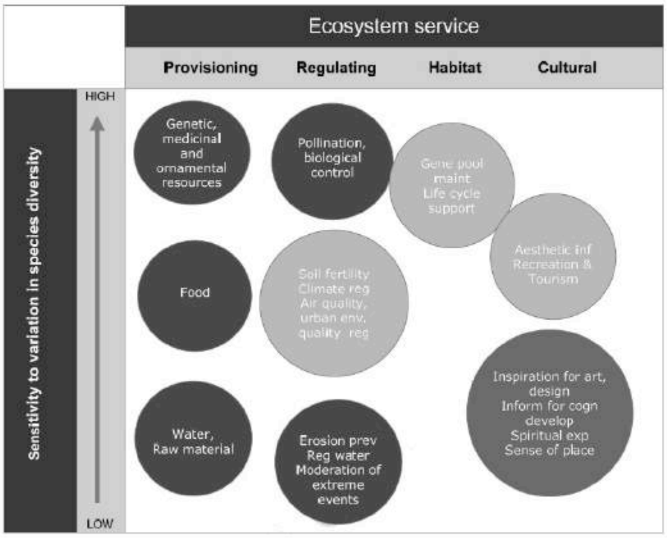

Figure 1. 1 –The several types of ecosystem services and their relation with species diversity, from Elmqvist, (2010).

Despite its significant ecological and economical value, biodiversity is being lost, and in some regions at a rapid rate (Díaz et al., 2006). Indirectly, this implies a decrease of ecosystem services provision, especially the ones more dependent on biodiversity (Figure 1.1) (Carpenter et al., 2009; EASAC, 2009). Over the last decades, biodiversity has been an important environmental and nature conservation issue. However, international initiatives and strategies aimed at halting the loss of biodiversity have failed in achieving their goals (Larigauderie et al., 2012). To cope with this, one of the ultimate reasons for biodiversity conservation is the real interest that people have in the societal benefits it generates, clearly explicit in the new Aichi biodiversity targets for 2020 (CBD, 2010). In 2011, the European Union (EU) adopted an ambitious strategy to halt the loss of biodiversity, acknowledging the value of ecosystems and the need to restore ecosystems for the benefit of both nature and society (EU, 2011). Although in this context biodiversity seems to be an anthropogenic and market concept, the truth is that if well managed, biodiversity and ecosystem services provision can promote a sustainable development and help to cope with biodiversity loss in the next decades (Maes et al., 2012). In this regard, IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) or TEEB are examples of joint initiatives that provide an interface between the scientific community, policymakers and NGOs, strengthening decisions on conservation and sustainability for both biodiversity and ecosystem services (Ring et al., 2010). However, some aspects of the relationship between biodiversity and ecosystem services are still unclear, namely to what extent biodiversity conservation ensures the provision of services (EASAC, 2009; Egoh *et al.*, 2009), and on how ensuring the provision of ecosystem services can(or not) support biodiversity conservation (Faith and Walker, 2002).

Forests are an important repository of terrestrial biodiversity and are responsible for the provision of important ecosystem services for human well-being (Figure 1.2), such as wood and non-wood forest products, water regulation, carbon sequestration, soil protection or recreation (Shvidenko et al., 2005). However, pressures such as conversion of forests into agricultural land, over-exploitation, the spread of invasive species, air pollution or climate change are causing great stress on forest ecosystems (Louman et al., 2010). The sustainable management of forest ecosystems may mitigate these degradation causes and also improve ecosystem services supply (MA, 2003).In particular, the EU policy for forestry is encouraging forest holders to adopt management plans that integrate biodiversity measures and support innovative funding mechanisms for the maintenance and restoration of ecosystem services that are generated by sustainably managed multifunctional forests (EU, 2013).

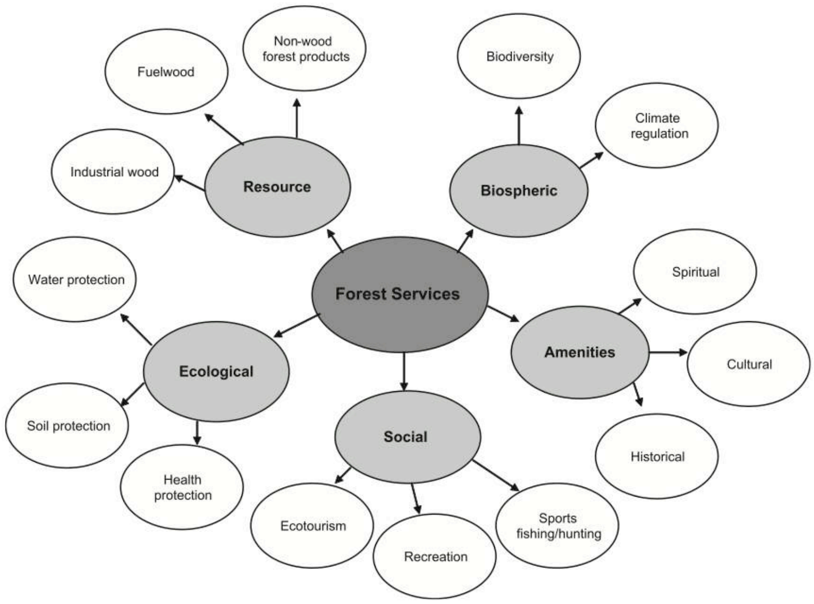

Figure 1. 2 - Forest ecosystem services organized by major classes, from Shvidenko et al., (2005).

Forests in Europe currently occupy about 40% of the land, and in Portugal this value is around 38% (Schutyser, 2010; FAO, 2013). In Portugal, cork oak, maritime pine and eucalypt represent more than 85% of the forest area, with the eucalyptus as the species with greatest representation (Pereira et al., 2011). Forests in Portugal provide common indirect services, such as carbon sequestration, soil protection or water regulation. In the northern and central parts of the country, pine and eucalypt stands contribute to wood and pulp production, respectively, and the eucalypt has expanded quickly since the 1960s when the paper industry took off (Carvalho Mendes, 2004). In the south, the *montado* (a savannah-like, oak agro-forest ecosystem) contributes to more than 50% of the worldwide cork production (Sá-Sousa, 2013). In Portugal, like in other Mediterranean regions, forests are expanding mainly as a result od succession following farmland abandonment, resulting in a positive reduction of soil erosion and river peak flows in winter (García-Ruiz et al., 2011). From an hydrological services perspective, this expansion should be managed considering the conflicts that may arise: (a) between forest growth and water yield in the drier regions, with a general decline in the total streamflow (Bredemeier, 2011); and (b) between forest biomass accumulation and fire hazard, especially when forests are composed by non-native species demanding more effective forest conservation and management strategies (Moreira et al., 2011; Fernandes, 2012).

Forests usually grow in regions with total annual precipitation above 500 mm (Chang, 2009). This indicates the strong connection between forest and water, with the latter determining tree species distribution. For instance, in Portugal the cork oak is mainly distributed in the south, but avoiding the driest areas, which are occupied by holm oak (Figure 1.3).

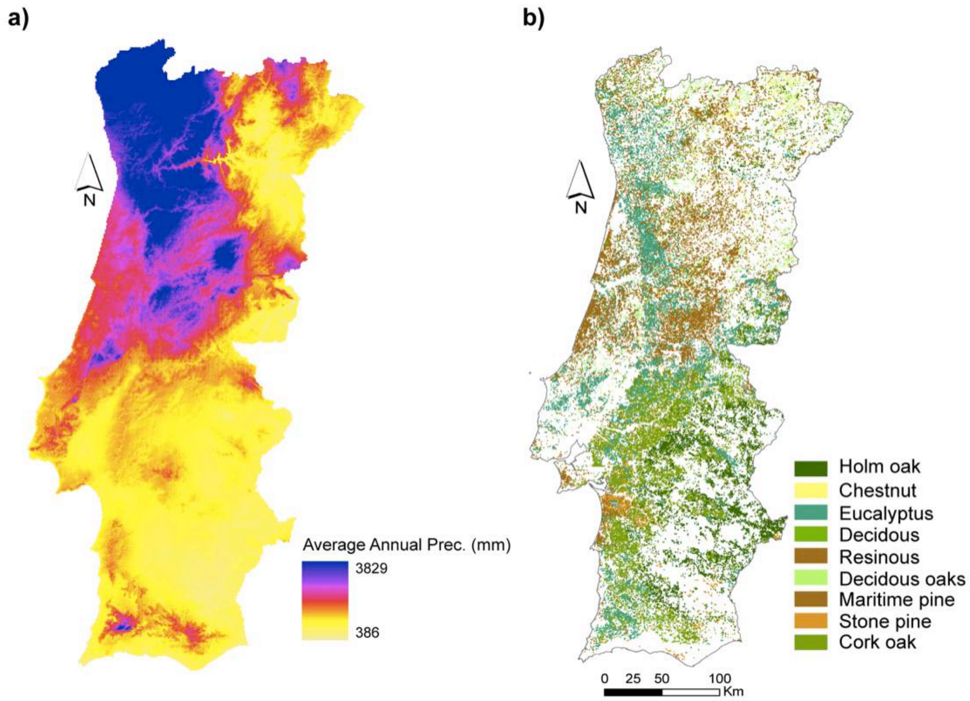

Figure 1. 3 – a) Average annual precipitation in Portugal (1961-90 average, from the SNIRH), and forest distribution in the country by dominant species (National Inventory of Forests, 2010).

1.2. Hydrological services and forests

1.2.1. Water and forests

Water plays an essential role in the functioning of ecosystems, underpinning biochemical cycles, supporting living organisms and their growth, and creating aquatic habitats on Earth (ChapinIII et al., 2002). More than 70% of the Earth's surface is covered by water, and in the atmosphere there is a layer of water vapour about 90 km thick (Chang, 2009). However, the distribution of water in the planet according to the different Earth systems is uneven (Figure 1.4).

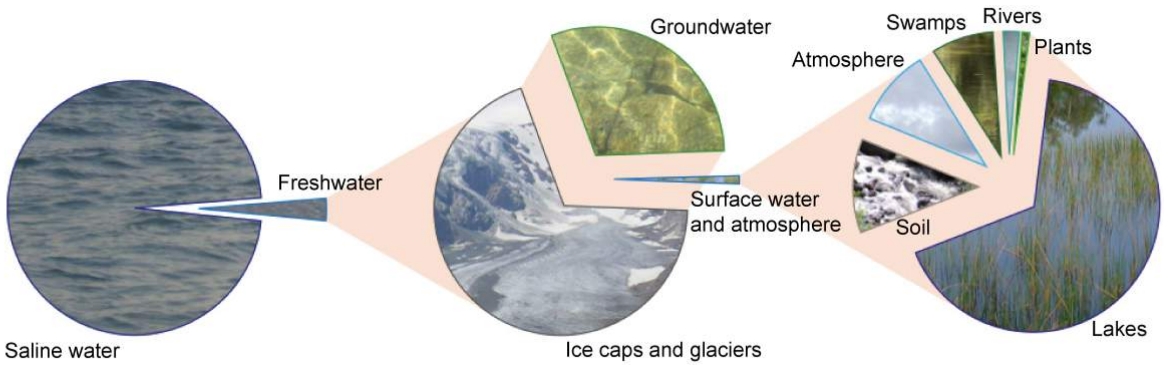

Figure 1. 4 – The world distribution of water.

Freshwater, the source of water for human needs, corresponds to only a small portion of the world's total water (Fetter & Fetter, 2001). Although not directly used by humans, oceans and glaciers, where the majority of water is located, play a rather important role in the water cycle (Figure 1.5).

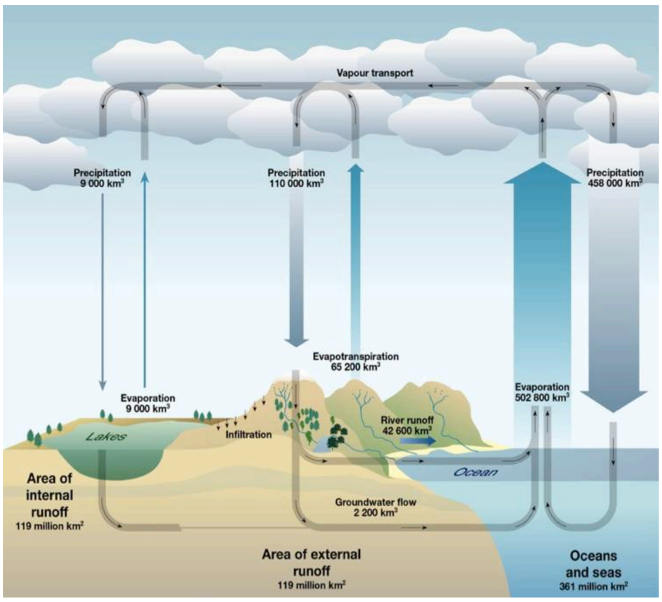

Figure 1. 5 – The water cycle, from Diop et al., (2002).

The water cycle, powered by solar radiation, is an essential process to support the dynamics of distribution and purification of water. It is based on the three physical states of water, thereby including a liquid phase, solid phase and gaseous phase (Diop et al., 2002). Water evaporates from the oceans and from the land surface to be transported and lifted into the atmosphere until it condenses and precipitates over land and oceans (Chow et al., 1988). The quantities of water vapour in the atmosphere are mainly obtained from the oceans, followed by evapotranspiration from land (living organisms and soil), and to a lesser extent from freshwater surfaces (Figure 1.5). Evapotranspiration from land returns about 65% of water back to the atmosphere (recycling moisture), which will then feed precipitation somewhere else (van der Ent et al., 2010). Precipitated water over land may be intercepted by vegetation, or when reaching the land surface, water can become either overland flow, or infiltrate into the ground flowing through the soil as surface flow or base flow to be discharged into the streams as runoff (Chow et al., 1988). From the precipitation that falls over land, about 35% returns to the oceans as water runoff and a small portion (2.5%) ends in land water surfaces (Gleick, 1993).

Plants have an active role in the water cycle, namely in water fluxes, such as evapotranspiration (transpiration and interception), throughfall and sediment transport (Kundzewicz, 2002). In particular, forests are considered the most prominent ecosystems interacting with water, due to their height, dense crown canopy, spread of the root system, wide horizontal distribution and vertical coverage (Calder, 2002; Chang, 2009). With forests, the occurrence, distribution and circulation of water are modified, the quality of water is enhanced and the timing of flow is altered (Chang, 2009). Forests and water are connected by physical and biological processes, so the management of forests affects the quantity, quality and timing of water (Jones et al., 2009) (Figure 1.6).

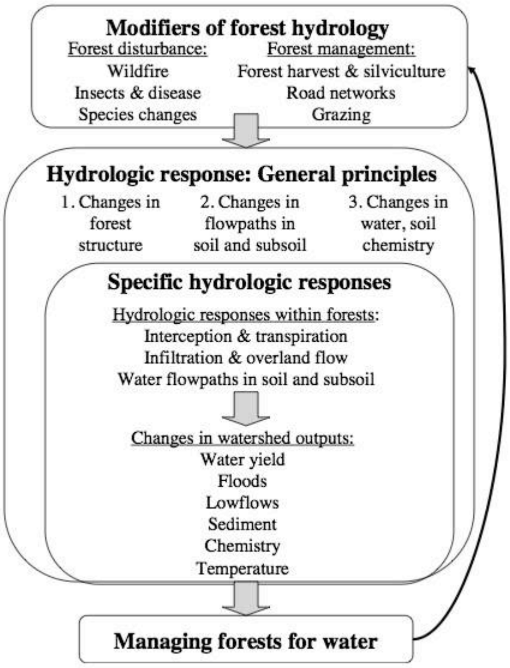

Figure 1. 6 - Hydrologic responses to changes in forest disturbance and management, from Jones et al. (2009).

Ecohydrology is the discipline that links both Hydrology (the study of the water processes) and Ecology (the study of the interactions between the living organisms and their environment), which has evolved since the 1990s following the growing demand for protecting rivers and streams (David M Harper, 2008). It proposes an integrative way of thinking, combining different disciplines seeking solutions for environmental problems related with water (e.g. water scarcity and allocation, floods and their consequences, water quality, eutrophication, soil erosion) (David M Harper, 2008; Vose et al., 2011). The perspectives created by this interdisciplinary view are improving the understanding of vegetation-water-nutrient connections to address the water resource issues (Newman et al., 2006; Vose et al., 2011). Parallel to Ecohydrology, Forest Hydrology is a discipline of Hydrology that studies specifically the relation of forest processes with all phases of the water cycle. However, it is restricted to forest ecosystems in an one-way influence, not considering the influence of water on vegetation growth (Chang, 2009). Studies reporting the interactions between water, biota and the physical conditions of the watershed have been done since several decades ago (Bosch & Hewlett, 1982; Kundzewicz, 2002). Those were traditionally supported by paired watershed studies with experiments in forested/non-forested watersheds, monitoring the effects of forest structure and composition on the storage and flow path of water (Jones et al., 2009). Figure 1.6 shows how forest modifiers, for instance a change in tree species, can influence the hydrologic responses of a watershed.

The broad scientific context of the research developed for this thesis is provided by Ecohydrology, complemented with Forest Hydrology regarding the influence of forest management options on water resources. This thesis applies an interdisciplinary approach to predict hydrological responses as a function of land cover and climate change, socio-economic and ecological factors (Vose et al., 2011; Le Maitre et al., 2014). This arises from the growing interest in understanding forest ecohydrological processes, in order to address water resource issues under the worldwide water crises and the on-going climate change debate (David M Harper, 2008; Vose et al., 2011).

1.2.2. From hydrological processes to hydrological services

As referred above, water regulation, carbon sequestration or pollination play an important role in the regulation of essential ecological processes and life support systems through biogeochemical cycles and other processes of the biosphere (de Groot et al., 2002; MA, 2003). Focusing on water and on the processes depending on water, a broad category of ecosystem services came up crossing the MA categories – the hydrological services, *i.e.* the water related benefits (Brauman et al., 2007). Examples of these benefits are the water supply for household use, mitigation of flood damages, cultural services, and water-related supporting services such as plant growth (Figure 1.7).

One of the most important driving forces acting on hydrological services is forest cover (Calder, 2002). There is a strong link between forests, soil and water, with forests often being compared to sponges due to their soil capacity of storing water (Calder, 2002; Lele, 2009). On the other hand, forests reduce the total annual water yield through their high rates of evapotranspiration to the atmosphere (Bosch & Hewlett, 1982). Positively, there is an increase of water infiltration into the ground, which depends on the canopy intersection (by precipitation and fog), soil characteristics and litter absorption processes (Figure 1.8). In addition, forests maintain water quality by enhancing soil stability and nutrient usage (Pattanayak, 2004; EASAC, 2009). Thus, promoting forestation actions in a watershed may ensure water supply for people and agricultural uses, as well as for hydroelectric power production (Figure 1.7). The benefits of water flow regulation however, may not be provided locally but transferred downstream (Guo et al., 2000).

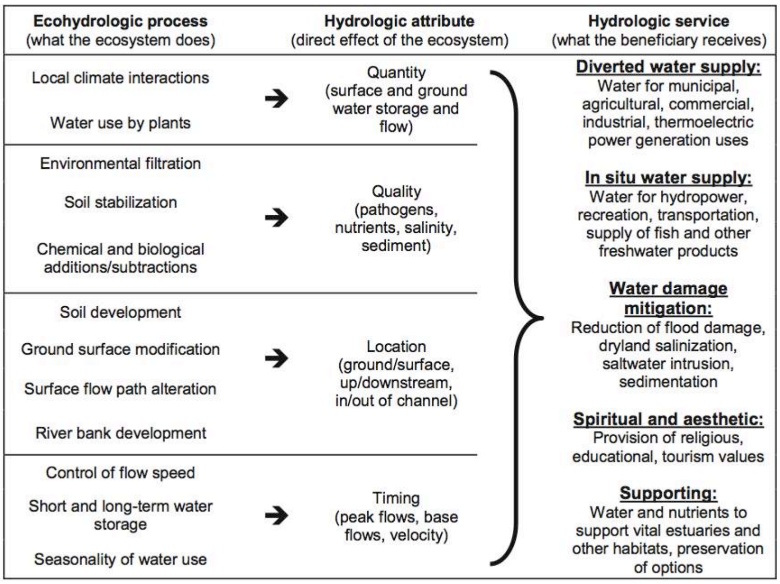

Figure 1. 7 -The relationship between the ecohydrological processes and the provision of hydrological services, connected by attributes such as of quantity, quality, location and timing, from Brauman et al. (2007).

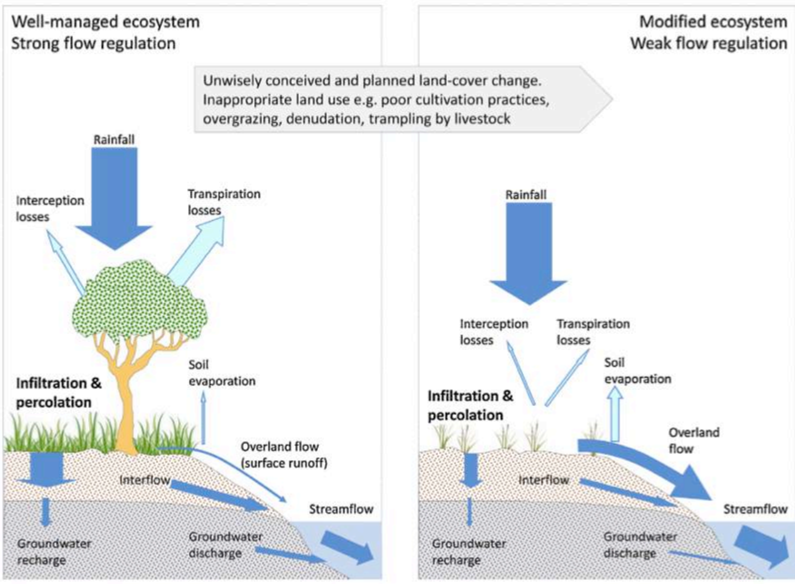

Figure 1. 8 – The movement of water from precipitation through the vegetation and soil system into streams, and how it is affected by changes in vegetation, from Le Maître, et al., (2014).

Overall, climatic, topographic and ecological conditions of the regions influence the water balance, with a significant role played by land cover, which can be targeted for ecosystem services management (Calder, 2002). Chapter 2 of this thesis addresses in more detail hydrological services provision and the relationships between forests and water.

1.3. Tools to analyse hydrological services

1.3.1. Approaches to model hydrological services

Mapping and modelling ecosystem condition is useful to deliver additional information about the quantity and quality of services that each ecosystem can provide, taking into account the site specific conditions determined by climate, geology and other natural factors, as well as the drivers and pressures affecting ecosystem services provision (Maes, 2014).The science and practice of hydrology includes evaluating, monitoring, assessing and forecasting the quantity, timing and quality of the water resources for a better water resource management and forecasting (Su et al., 2012). Thus, it is essential to understand the water cycle with its respective climate and ecosystem interactions (David M Harper, 2008; Su et al., 2012).

Two different approaches for modelling hydrological services exist: (i) traditional hydrological tools, such as SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998); and (ii) new ecosystem services oriented tools, such as InVEST (Integrated Tool to Value Ecosystem Services) (Tallis & Polasky, 2009) or ARIES (Artificial Intelligence for Ecosystem Services) (Villa et al., 2009). Traditional hydrological tools are based on robust daily-runoff hydrological models at the watershed scale, requiring detailed datasets and expert knowledge. Conversely, new ecosystem services tools are based on ecosystem services indicators and models across large scales, they are more accessible for non-experts users, and they provide a more integrative picture because it considers the demands for the service (Vigerstol & Aukema, 2011). A review of several ecosystem services tools with their respective advantages and disadvantages can be found in (Bagstad et al., 2013). Despite being rare on ecosystem services literature until now, since they analyse mainly ecosystem functions rather than ecosystem services, daily rainfall-runoff models are more robust to model and mapping the water flow and quality (Crossman et al., 2013). However, additional studies to analyse the demands of the services are needed for a complete ecosystem services evaluation (Schröter et al., 2014). In chapter 2 of this thesis, an ecosystem service oriented tool was applied to illustrate a novel framework to analyse hydrological services provided by forests. In Chapter 4, a hydrological modelling tool was used to evaluate the effects of land cover/use and climate change on hydrological services provision.

1.3.2. The SWAT hydrological model

Hydrological models are powerful tools for simulating the effects of management and climate on water resources (Jayakrishnan et al., 2005). However, they are approximations of reality that should be improved and evaluated against uncertainty (Chow et al., 1988;

Moriasi et al., 2007). The modelling of hydrological processes has evolved following two basic forms: (a) physical models, in which the processes are modelled according to fundamental physical laws; and (b) empirical models, in which the relationships are derived from measured data (Trimble, 2009). Hydrological models can also be classified according to the process approach: (a) deterministic models, in which a given input always produces the same output; or (b) stochastic models that consider the randomness of the variables using probabilistic distributions of each variable to generate random values (Chow et al., 1988). They can also be divided in: (a) lumped models, not considering the spatial variability, with the results being averaged according to the dominant characteristics of the watershed; or (b) distributed, in which models account for the spatial variability of conditions that occur in the watershed (Trimble, 2009).

SWAT is a physically based, deterministic and semi-distributed hydrological model, developed by the United States Department of Agriculture to assess the impact of management on water supplies and non-point source water pollution in a watershed or large river basins (Arnold et al., 1998). Its progress was due to the development of databases (e.g. on soil properties) and the creation of several GIS (Geographic Information System) interface tools to support the input and output of data for detailed spatially distributed analysis of hydrologic and water resources systems (Arnold & Fohrer, 2005; Jayakrishnan et al., 2005). One of the most popular GIS interfaces is ArcSWAT, which runs in the ArcGIS software (ESRI), and uses to a geodatabase model to store SWAT input and output data (geographic, numeric, text) in an organized way (Olivera et al., 2006). Major model components include weather, hydrology, soil temperature and properties, plant growth, land management, nutrients, pesticides, bacteria and pathogens, being capable of continuous simulation over long time periods (Gassman et al., 2007). The major unit of simulation is the river basin and SWAT is prepared to run in either medium watersheds (above 100km^2) until very large basins. River basins have a hierarchical structure and natural boundaries, turning them into a suitable scale for integrated ecohydrological studies and modelling (Krysanova & Arnold, 2008).

In SWAT, the hydrological cycle is based on the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where $_t$ is the simulation period, SW_t is the soil water content after the simulation period, SW_0 is the soil water content at day i (beginning of the simulation period), R_{day} is the amount of precipitation, Q_{surf} is the amount of surface runoff, E_a is the amount of evapotranspiration, W_{seep} is the amount of water entering the vadose zone, and finally Q_{gw} is the amount of return flow, all at day i (Neitsch et al., 2011).

The overall hydrologic balance is simulated for each Hydrological Response Unit (HRU), including canopy interception of precipitation, partitioning of precipitation, snowmelt water, and irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers (Gassman et al., 2007). Surface runoff is calculated using an empirical model, the SCS curve number method, based on 20 years of studies in the United States involving rainfall-runoff relationships in several land use and soil types (Neitsch et al., 2011). Soil erosion is calculated using a Modified version of the USLE (Universal Soil Loss Equation).

Figure 1.9 represents schematically the steps that are needed to run the model in the ArcSWAT interface. First, the watershed is delineated and divided into sub-basins using a digital elevation model (DEM). Then, each sub-basin is divided into HRUs, based on unique combinations of land cover, soil and slope attributes, improving the accuracy of predicted loadings from the sub-basin (Arnold et al., 2011). Although HRUs are geographical units, their spatial position in each sub-basin merely represents the sum of the total contribution of each unique combination for the model outputs: they correspond to scattered land pieces in a sub-basin, without spatial interactions between them (Neitsch et al., 2011). This is important, for instance, for sediment or nutrient loadings, in which the loadings of a given HRU do not pass to the HRU immediately adjacent, but are added to the sum of the loadings of all the HRUs within a given sub-basin (Arnold et al., 2011).

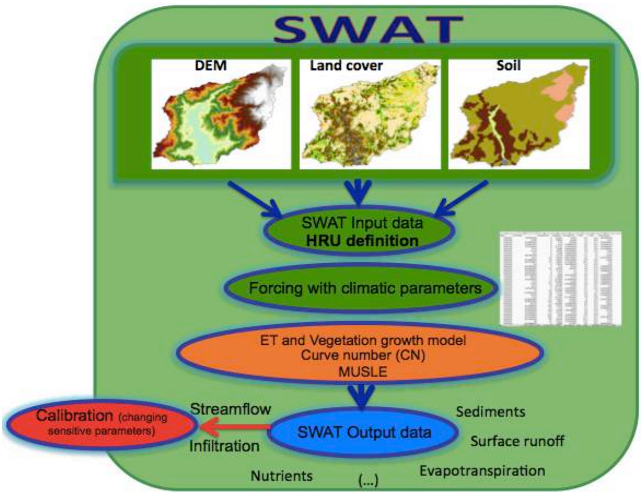

Figure 1. 9 – Simple schematic flow of the steps required in ArcSWAT**.**

Subsequently, the model is forced with daily climatic data (precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed) (Figure 1.9). These daily climatic inputs can be obtained either from historical records, *e.g.* in Portugal from

SNIRH (National System of Water Resources Information) or IPMA (Portuguese Institute of the Sea and Atmosphere), and/or generated internally in the model using a weather generator tool, with the first option being preferred for optimal model performance (Neitsch et al., 2011). Here, the important condition is to have a good climatic dataset without gaps, mainly for precipitation representativeness and model performance (Stisen et al., 2012). For this, data gap filling is an important step, using for instance, regression analysis by correlations with the nearest weather stations with complete records.

The calibration process (Figure 1.9) consists in changing sensitive parameter values to minimize the deviation between observed and simulated values of discharge (mandatory), sediments, nitrates, and total phosphorus, just to mention the most common (Moriasi et al., 2007). Calibration can be made manually in a trial error exercise, which is time consuming, or using sensitivity analysis software, such as SWATCUP (Abbaspour, 2013) or SWAT's auto-calibration tool (van Griensven, 2005). The main advantage of the first is that users can control better the processes inside the model, whereas with sensitivity analysis tools users should be well informed about the processes in the model to understand the changing in the parameters.

After calibration, a validation procedure should be done to assess the performance of the calibrated parameters for an independent set of data in a different time period, with no further adjustment of parameters (Arnold et al., 2011). The performance of the model can be evaluated by graphical techniques, and it is recommended using at least three quantitative statistics: (i) Coefficient of determination that describes the degree of collinearity between simulated and measured data (R^2), ranging from -1 to 1; (ii) Nash-Sutcliffe efficiency (NSE) that measures the variability of the model residuals with respect to the variability of the observations, comparing the performance of the hydrological model to that of a hypothetical model that yields as predictions the mean value of the observations (value 1 indicates equal model performance); and (iii) the per cent bias (PBIAS) that measures the deviation (%) with simulated data in respect to the observed data (0.0 indicates no deviation) (Moriasi et al., 2007; Morán-Tejeda et al., 2013). The respective equations are described in Appendix B, and the performance rates can be found in Moriasi et al. (2007).

SWAT has gained international acceptance as a robust interdisciplinary watershed-modeling tool since the late 1990s, with an annual international conference dedicated specifically to SWAT topics organized since 2003 (Gassman et al., 2007). SWAT has been used for many different applications, including (not exclusively): land use change impacts (Baker & Miller, 2013; Wagner et al., 2013; Yan et al., 2013); climate change (Nunes et al., 2008; Raposo et al., 2013; Zabaleta et al., 2014), combined climate with land use change (Mango et al., 2011; Kim et al., 2013; Shi et al., 2013; Khoi & Suetsugi, 2014); water quality (Moriasi et al., 2013; Narula & Gosain, 2013; Chen et al., 2014); soil erosion (Ullrich & Volk, 2009; Ouyang et al., 2010; Zhang et al., 2014); and ecosystem services (Quintero et al., 2009; Notter et al., 2012; Liu et al., 2013; Logsdon & Chaubey, 2013). In the last 5 years, the number of publications using SWAT has increased exponentially, highlighting the year of 2013 with the highest number of published articles (292), and 2014 with already 137 published articles, according to the SWAT literature database (SWAT, 2014). The same database includes 11 peer reviewed published articles in Portugal using SWAT, starting in 2008 with paper on hydrological processes under climate change (Nunes et al., 2008), but recently mainly about water quality issues (Demirel et al., 2009; Yevenes & Mannaerts, 2011; Ferreira et al., 2014; Mateus et al., 2014). Therefore, the application of SWAT to study the effects of land cover/use and climate changes on hydrological services, as well as its application to a watershed in northwest Portugal, are novel and an important contribution to the literature. Chapters 4 and 5 of this thesis describe and discuss the main results from such studies.

1.3.3. Remote sensing for eco-hydrological assessment

Remote sensing data and products have been successfully used to map and model the structural and functional attributes of ecosystems, allowing to overcome limitations related to spatial and temporal scales of resolution (de Jong et al., 2004). Broadly defined, Remote Sensing is the process of getting information about an object, area, region or phenomenon without physical contact with it (Lillesand et al., 2004). This broad definition would encompass, among others, space probes, most of medical imaging, non-destructive testing, sonar, as well as instruments observing the earth from a distance (Schott, 2007). The latter, commonly known as Earth Observation, refers to the detection and interpretation of the electromagnetic energy of different objects from aircrafts or satellites (Turner et al., 2003; Chang, 2009). They are used for global change studies and environmental monitoring, and satellites with different instruments able to sense different wavelengths, which can be useful for meteorological, atmospheric, land, water, biodiversity, gravimetric, topographic and soil purposes (Lillesand et al., 2004; Schott, 2007). The different features of the Earth surface and atmosphere will absorb, emit or reflect the electromagnetic radiation from the sun, which can be sensed by different instruments on board of satellites and aircrafts (de Jong et al., 2004). The electromagnetic spectrum can be divided into optical wavelengths (between 0.4 and 14 μm) and longer wavelengths known as microwave (between 1mm and 1m) in one or more bands (Figure 1.10).

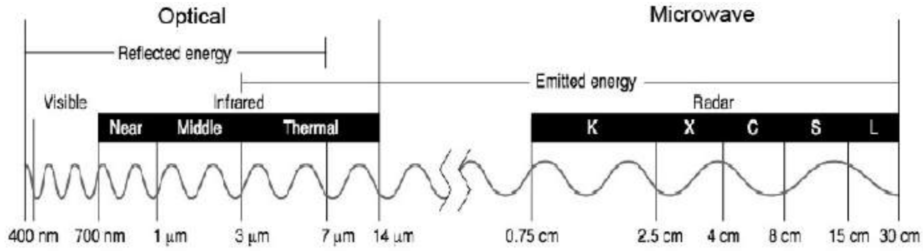

Figure 1. 10 – Spectral characteristics of the electromagnetic spectrum, from Tuner et al., (2008).

The system of data acquisition can be: (a) passive, in which sensors detect the naturally emitted microwave energy, related e.g. to the temperature and moisture properties of the emitting object (Figure 1.11); examples are optical images from multispectral and hyperspectral scanners (Lillesand et al., 2004). Or (b) active when sensors provide their own source of radiation, emitting a pulse and measuring the energy returned back to a detector (Turner et al., 2003; de Jong et al., 2004); examples of active systems are: Radar, Lidar, Syntetic Aperture Radar (SAR), Interferometry radar (Lillesand et al., 2004). Satellites may be grouped in those with: (a) circular orbits, such as Low Earth Orbits (LEO), with moderate to high temporal and spatial resolutions (e.g. Landsat, TERRA, NOAA satellites); and (b) a geostationary orbit at the equator (GEO), located at 40 times higher altitude than LEO satellites and with a 24hour period, commonly used for weather reports (Schott, 2007).

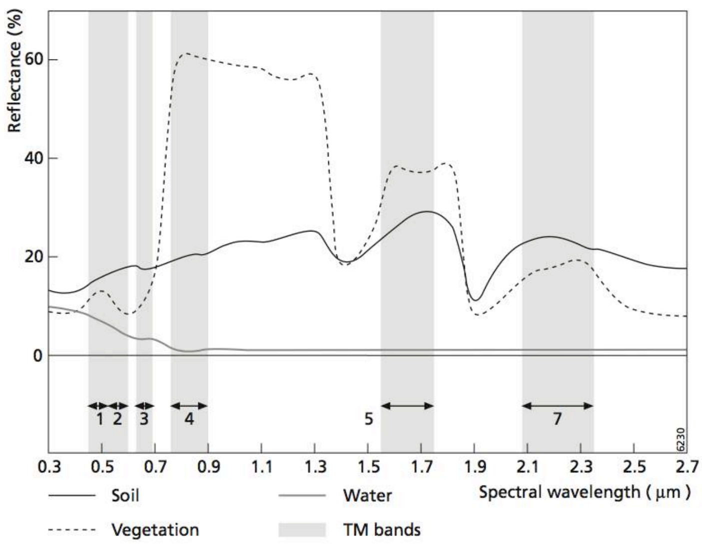

Figure 1. 11 - Typical spectral reflectance curves for water, soil and vegetation, from de Jong et al., (2004).

Data and information created form Earth Observations are an important input to advance the understanding of the Earth's systems, regarding weather, climate, oceans, land, geology, natural resources, natural hazards and ecosystem functioning (Unit, 2013). Examples of satellites with useful products are manifold, from Landsat missions, to the NOAA (National Oceanic Atmospheric Administration – USA) geostationary weather satellites (Carvalho-Santos et al., 2013). Also GNSS (Global Navigation Satellite Systems) signals (refracted, reflected and scattered) can be successfully used for environmental applications, such as snow cover and ice thickness, vegetation productivity or soil moisture, beyond the traditional application on georeferencing (Jin et al., 2011). Very recently (April 2014), Europe has launched the Sentinel-1, the first of a constellation of six family satellites from an ambitious Earth observation project (Copernicus), which has the mission of long-term monitoring the planet's land, water and atmosphere (Butler, 2014).

Earth observation has several strengths, such as: (i) the homogenization of the global Earth views, allowing the complementarity of several products to deliver a more efficient description of objects or phenomena; and (ii) the temporal frequency of the observations, enabling the characterization of the full range of natural phenomena, associated to the growing spatial resolutions (Morel, 2013). However, some challenges can be pointed out when working with satellite data, such as the extensive work and studies demanded to interpret the results in earlier phases of research (making some products expensive), associated to the large errors that need calibration and validation with ground observations, as well as correction, especially the imaging products because of the cloudless and contamination of the signal through the atmosphere (Turner et al., 2003).

In a world with growing global environmental change, Earth observation has great potential for applied ecology, improving the ability of monitoring the state of biodiversity and ecosystem functioning (Pettorelli et al., 2014). From land cover classifications, to the estimation of Net Primary Productivity, climatic parameters or soil moisture, the applications are widely recognized to understand and monitor the pathways and drivers of environmental change (Kerr & Ostrovsky, 2003; Turner et al., 2003). Likewise, satellite products are also being used in ecosystem services studies, helping in the quantification and mapping of supplies and demands of ecosystem services to support decision-making processes (Ayanu et al., 2012).

Satellite products have been used for hydrological evaluation since the beginning of the 1980s, with the first Landsat images and weather predictors from satellite observations (Pietroniro & Prowse, 2002; van Dijk & Renzullo, 2011). Traditionally, for water resource analysis and modelling, observations are mainly coming from *in situ* measurements by ground instruments (e.g. meteorological and hydrometric parameters), which usually require some maintenance and a dense spatial cover network to shape the hydrological processes (Chow et al., 1988). In fact, *in situ* observations are essential for calibration and validation of satellite products (Tang et al., 2009). However, advantages from the use of satellite products on hydrological processes, using passive or active satellite systems, are well recognized. In the literature there are several reviews about the potential and actual use of satellite observations in hydrology (Kite & Pietroniro, 1996; Rango & Ahlam, 1998; Pietroniro &

Prowse, 2002; Schmugge et al., 2002; van Dijk & Renzullo, 2011; Fernández-Prieto et al., 2012; Su et al., 2012). In Chapter 3 of this thesis, a review of satellite applications for hydrological services assessment is presented, focusing more on ecosystem function and on the capacity of the system in providing those services.

1.4. Scope, objectives and thesis structure

1.4.1. Scope

Due to their interactions with the water cycle, ecosystems provide hydrological services, namely water supply and water damage mitigation, which are essential for human well-being (MA, 2003; Brauman et al., 2007). Concerns about water problems and sustained provision of hydrological services have been increasing over the last decades, with a special emphasis for water scarcity (UN, 2011). For an effective management and planning of water resources, hydrological services should therefore be adequately conceptualized, quantified, mapped and monitored.

Forests are among the most important ecosystems for the provision of hydrological services (Calder, 2002). Because forests may play different hydrological roles according to the environmental characteristics of each region, it is important to model how forests will contribute to the provision of hydrological services. Likewise, climate has a strong influence on hydrological services. Therefore, it is important to consider future climate projections together with land cover change for a complete understanding of the interactions that may trigger alterations in the provision of hydrological services (Shi et al., 2013; Khoi & Suetsugi, 2014). In addition, land planning at the watershed level should be considered for a more effective management of hydrological services, as well as of other services and biodiversity conservation. In this case, the potential for managing land cover according to the best options is a useful asset for decision makers (Egoh et al., 2008; Reyers et al., 2009; Zanchi et al., 2014).

1.4.2. Objectives

The overarching objective of this research is to **develop improved conceptual and analytical frameworks to assess the hydrological ecosystem services provided by forests, thereby supporting options for spatial planning and land management**. The research was developed under four linked specific objectives, and comprises a case study in northern Portugal and two in the Vez watershed, northwest Portugal. The research developed under each specific objective resulted in one published (or submitted) scientific manuscript with international peer reviewing and circulation.

The four objectives and their associated research questions are:

1) To improve the conceptualization of hydrological services provided by forests

- i) How can hydrological services be defined and what are their specific relations with the water flows and with forests ecosystems?
- ii) What are the best indicators to measure the provision of hydrological services?
- iii) How can the conceptualization of hydrological services be useful for planning and management?

2) To provide a review of remote sensing data and products applied to hydrological services

- i) What types of satellite data and products are available for hydrological services evaluation?
- ii) To what extent can the evaluation of hydrological services benefit from the use of satellite products?
- iii) How can hydrological modelling and satellite products be integrated?

3) To analyse of how hydrological services are influenced by both land cover change and future climate conditions

- i) To what extent can the provision of hydrological services be modified by land cover change, and particularly through afforestation?
- ii) How will future climate influence the provision of hydrological services at the watershed level?
- iii) Is there any combined effect of land cover and future climate conditions on the provision of hydrological services at the watershed level?

4) To analyse trade-offs and synergies between different forest ecosystem services and biodiversity conservation

i) Where in the watershed are forest ecosystem services provided?

ii) How can afforestation processes that promote hydrological services affect biodiversity in a watershed context?

iii) In a spatial planning context, how can we harmonize landscape afforestation with biodiversity conservation?

1.4.3. Thesis structure

Analysing hydrological services provided by forests is a topic that combines principles and methods of eco-hydrology with concepts and methods from the novel ecosystem services science. The dimensions of the analysis encompass the acquisition of the conceptual foundations from both sciences, being able to operate with them, as well as a description of ways for evaluating and monitor hydrological services provision. Moreover, it should also encompass the use of modelling tools to be able to understand (and predict) hydrological processes and their links to the ecological functions of ecosystems.

This thesis is organized in six chapters. **Chapter 1** provides a general introduction to all the topics approached in the thesis, which is fundamental to support the workflow and knowledge presented. It includes the statement of research objectives as well as this description of the thesis structure.

The main results of the research developed for the thesis are presented in chapters 2 to 5. **Chapter 2** develops a conceptual framework for provision of hydrological services based on the relations between water and forests, in the context of socio-ecological system analysis. In addition, the conceptual framework is illustrated for the water supply and soil erosion control services applied to a case study in northern Portugal. **Chapter 3** presents an overview of satellite products that can be used to evaluate and monitor the provision of hydrological services, based on the different water compartments on Earth (atmosphere, cryosphere, surface water, soil, ground and vegetation). The usefulness of those products for hydrological modelling is also addressed. **Chapter 4** applies the SWAT hydrological model in the Vez watershed, northwest Portugal, to analyse the provision of hydrological services (as defined in Chapter 2) under scenarios of land cover change and future climate conditions. **Chapter 5** uses the spatial outputs from SWAT simulations (developed in Chapter 4), together with a biodiversity value map, to analyse the trade-offs and synergies to support land planning and management at the watershed level.

Finally, **Chapter 6** provides an integrative discussion of the results and key findings from the previous chapters as well as some overarching conclusions and guidelines for future research on the provision of hydrological services by forests under a land planning and management framework.

Chapter 2

Hydrological services and the role of forests: Conceptualization and indicator-based analysis with an illustration at a regional scale

Abstract

Forests are among the most important ecosystems for the provision of hydrological services. These include water supply and water damage mitigation, in the dimensions of quantity, timing and quality. Although the hydrological role of forests is well documented in literature, a conceptual framework integrating these three dimensions is still missing. In this study, a comprehensive conceptual framework to improve the assessment of hydrological services provided by forests was developed. In addition, the framework was tested by an illustration for northern Portugal, a region with both Mediterranean and Atlantic climatic influences.

The TEEB (The Economics of Ecosystems and Biodiversity) framework of ecosystem services was adapted to the relation between forests and water. Then, this new framework was complemented with a set of spatially explicit indicators that quantify the supply and demand of hydrological services. In addition, the implications of the framework were discussed in the context of the social-ecological systems, using the DPSIR (Drivers, Pressures, State, Impacts and Responses) model. Finally, the framework and the indicators were illustrated for northern Portugal using the water supply (quantity) and soil erosion control as examples.

Results show that the proposed conceptual framework is a useful tool to support land planning and forest management, adapting the provision of hydrological services to the regional biophysical and social conditions. The test of the framework across a heterogeneous region suggests that a spatially explicit combination of system property, function, service and benefit indicators can be an effective way of analysing and managing the supply and demand of the hydrological services.

Keywords: Hydrological services; Conceptual framework; Forests; Indicators; Northern Portugal; Social-ecological systems.

Carvalho-Santos C., Hein L., Honrado J. (2014) Hydrological services and the role of forests: Conceptualization and indicator-based analysis with an illustration at a regional scale. Ecological Complexity. 20: 69-80.

2.1. Introduction

Hydrological services, or the water-related services provided by ecosystems, are considered crucial for human well-being (MA, 2003). As defined by Brauman et al. (2007), hydrological services encompass the benefits to people derived from the regulation of water flows by ecosystems. They include a large group of services: water supply (diverted and in situ supply), water damage mitigation, water-related cultural services and water-associated supporting services. The provision of hydrological services is usually analysed according to three dimensions: (i) quantity (i.e. total water yield), (ii) timing (i.e. seasonal distribution of the flow) and (iii) quality (i.e. removal and breakdown of pollutants and trapping of sediments) (Brauman et al., 2007; Elmqvist et al., 2009).

Any ecosystem is potentially important to the provision of hydrological services, but forests are considered the main contributors (Calder, 2002). Forests (soil and vegetation) promote infiltration, increasing soil moisture content, groundwater recharge and the gradual release of water (Bruijnzeel, 2004). Some benefits are associated to this water storage and gradual release, such as hydropower generation and water supply for households (Guo et al., 2000; Brown et al., 2005; Farley et al., 2005; Brauman et al., 2007). In addition, due to the intervention of tree canopies and root system, surface runoff is low, maintaining soil stability and improving water quality in terms of sediments (Ilstedt et al., 2007; Lele, 2009). Furthermore, there is evidence that the existence of forests contributes to moderate water-related hazards, such as floods and landslides (Calder & Aylward, 2006; Bredemeier, 2011). However, forests may reduce the annual water yield through increased loss by evapotranspiration, and consequently limit the amount of water available in the system (Bosch & Hewlett, 1982; Sahin & Hall, 1996; Bruijnzeel, 2004; van Dijk & Keenan, 2007; Bredemeier, 2011). One important note is that the magnitude of forest influencing hydrological services described before is very site dependent (Calder, 2002).

Despite recent advances in understanding the role of forests in the provision of hydrological services, there are still a number of conceptual questions remaining. These include the specific components of the hydrological service, how these components can fit in the ecosystem services framework proposed in the context of the TEEB [The Economics of Ecosystems and Biodiversity] project (Haines-Young & Potschin, 2010; de Groot et al., 2010a), and how can these components be quantified and mapped.

In order to address these questions, the objective of this article is to develop a conceptual framework for understanding the hydrological services and describing the role of forests in providing hydrological services. The conceptual framework is illustrated at the regional scale using northern Portugal as a case-study region.

Forests in northern Portugal have distinct composition, structure, functioning and spatial distribution according to the prevailing Mediterranean or Atlantic influences (Costa et al., 1998) for which hydrological effects can be compared. Special attention is given to Mediterranean forests because here the different aspects of climate, land use and soils are very related to water availability (García-Ruiz et al., 2011). Typically in Mediterranean areas water is scarce in summer, which often results in serious water stress (Nunes et al., 2008). Therefore, assessing the role of these forests in the water cycle is an interesting context to test the possible applications of the conceptual framework for hydrological services provided by forests.

The paper is structured as follows. First a conceptual framework to analyse the provision of hydrological services by forests was developed, based on the TEEB ecosystem services framework and on further literature review. Also, a set of indicators to quantify hydrological services was derived from the framework. In addition, an extension of the framework was suggested in the context of social-ecological systems theory. Finally, the framework was illustrated using indicators to analyse the spatial distribution of water supply (quantity) and water damage mitigation (soil erosion control) at a regional scale for northern Portugal.

2.2. Conceptual framework for hydrological services

2.2.1. Conceptual framework

The TEEB project combined insights on the loss of biodiversity, the degradation of ecosystems and changes in the supply of ecosystem services, and analysed the ecological, social and economic implications of ecosystem degradation (de Groot et al., 2010a). Accordingly, the TEEB conceptual framework, which is based on the cascade diagram of ecosystem services (Haines-Young & Potschin, 2010), classifies services on the basis of the link between ecosystems and the social-cultural dimensions of human well-being (de Groot et al., 2010a). This cascade considers a stepwise description of properties and functions, related to the biophysical system, which provides potential services to support the social systems through concrete benefits (Haines-Young & Potschin, 2010). In order to improve our understanding of the provision of hydrological services by forests, a specific framework was proposed based on the one presented in TEEB. The biophysical functions behind the relation between forests and water, as well as the resulting contributions to human well-being were highlighted (Figure 2.1).

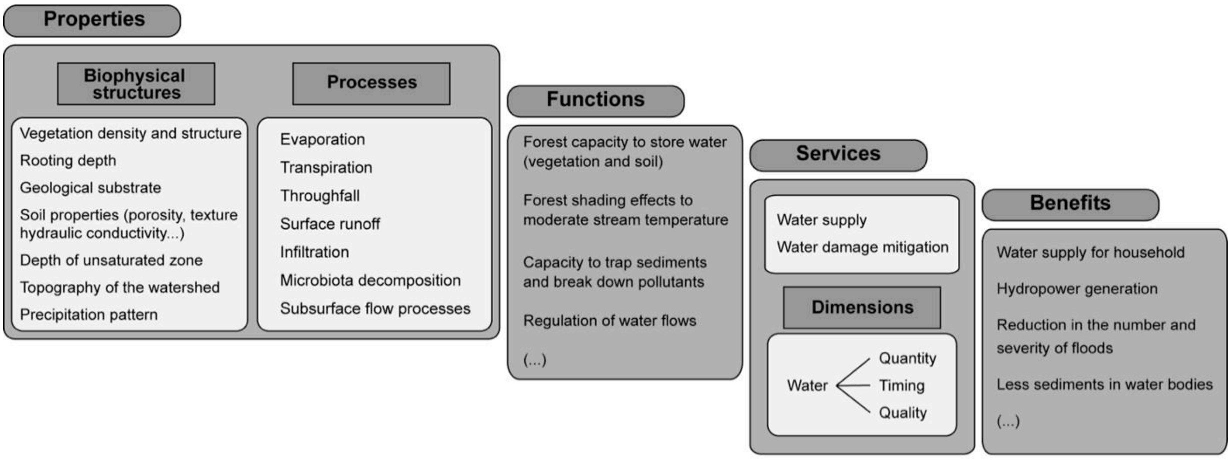

Figure 2. 1 - Conceptual framework for hydrological services provision by forests, showing the relationship between the biophysical ecosystem (properties and functions) and the social system (services and benefits). Inside boxes are some examples of each step of the framework. Adapted from the ecosystem services framework by de Groot et al. (2010b) and Haines-Young & Potschin (2010).

Forests regulate the water cycle. This major function, however, only becomes a service when people use or experience the water benefits resulting from this regulation, such as water supply for household or hydropower generation (Figure 2.1). Fundamental attributes of ecosystems (properties) provide the mechanisms responsible for generating potential services (de Groot et al., 2010b). Underlying ecosystem properties, biophysical structures are the platforms where processes occur (Fisher et al., 2009). For instance, the roots of trees and shrubs promote porosity in forest soils thereby improving the infiltration process (Figure 2.1). Functions are the result of such properties, and determine the capacity of the ecosystems to provide services and ultimately benefits. This intrinsic capacity exists independently of whether people use or feel the services, which is only materialized when a beneficiary is identified (Haines-Young & Potschin, 2010). For example, the function of water flow regulation will improve human well-being by reducing the number and severity of floods. This becomes a service only if there are people benefitting from the reduced flood risk (Figure 2.1). Note that the relation between ecosystem functions and services may be complex, with functions potentially contributing to multiple services (as in the case of regulation of water flows allowing both seasonal water supply and water damage mitigation) (Ansink et al., 2008). Services are the pure aspects of ecosystems utilized by humans contributing to their welfare (e.g. water supply), while the benefits are the actual and sometimes transformed advantages to people´s well-being (e.g. drinking water for household) (Boyd & Banzhaf, 2007; Fisher et al., 2009). From one service multiple benefits may be derived, which are the fundamental units to establish valuation. Therefore, benefits translate a welfare gain that can, in principle, be valued on ecological, social and economic grounds (Lele, 2009). In our adapted framework attention was not given to the values of hydrological services, being the purpose of this paper to examine the biophysical relations between forests and water.

From the typology of hydrological services proposed by Brauman et al. (2007), the ones that are directly linked to the flow of water through forests were selected. Therefore, the hydrological services provided by forests that are accounted here are (i) water supply and (ii) water damage mitigation, both considered according to the three dimensions of hydrological services: quantity, timing and quality. Water supply, a provisioning service in the Millennium Ecosystem Assessment classification (MA, 2003), includes private and public water-use (irrigation, industry, urban), hydropower generation and flow of water for transportation, whereas water damage mitigation includes the regulation of floods and the reduction of soil erosion by water (Brauman et al., 2007). The complex interactions between forests and water will be developed in the next section according to the three dimensions of hydrological services. The focus will be on the provision of services by different vegetation/land cover types, comparing forests with non-forested areas (see table 2.1 for synthesis).

2.2.2. Dimensions of hydrological services and their relation to forests

2.2.2.1. Water quantity

An increase in plant leaf area, associated with forest expansion, generally means higher rates of evapotranspiration and consequently a reduction of water available for recharge (Zhang et al., 2001). This reduction may negatively affect the water supply service, but may also be beneficial for water damage mitigation (Brauman et al., 2007). The decrease of water surplus in rainy tropical regions is a benefit to control water hazards, so forest should be composed by high water demanding vegetation (van Dijk & Keenan, 2007). On the other hand, in regions where water is a limiting factor, as in most of the Mediterranean, the impacts of increased evaporation of intercepted water should be considered before forest plantation, and the use of low water demanding vegetation should be encouraged to avoid water scarcity (Gallart & Llorens, 2004).

In the hydrology literature, the relation between forests and water quantity at a watershed scale has been analysed using paired-catchments studies. These studies have shown that there is often an increase in water yield when forests are replaced by other type of vegetation, e.g. grasslands (Bosch & Hewlett, 1982; Brown et al., 2005). Studies conducted all over the world (compilation of data from 145 experiments) revealed that, with a reduction of 10% of conifer or deciduous hardwood cover, the water yield increased on average by 20-25mm and 17-19mm, respectively, even though there are significant local variations (Sahin & Hall, 1996). Considering the reverse situation, when forests replace other types of vegetation cover, the common measure to detect changes in water quantity is either annual runoff reduction or water yield reduction. In a review of 26 global catchments, annual runoff decreased about 44% where grasslands were forested, and 31% where scrublands were forested (Farley et al., 2005). A compilation of French literature for the Mediterranean has shown that, after clear-cutting or fire, annual runoff typically increased with 10%, and that after afforestation annual runoff decreased again (Cosandey et al., 2005).

From a broader perspective, forests may contribute to increase the amount of water available, either by improving infiltration, contributing to atmospheric moisture by evapotranspiration or by fog interception (van Dijk & Keenan, 2007). There is a trade-off between what is a decrease in the total water yield and the improved infiltration under forest cover that contributes to gain water (Malmer et al., 2010). Some authors even discuss that the benefits of increased infiltration may compensate the costs of losing water in some specific locations, such in the tropical regions (Bonell & Bruijnzeel, 2005). Other authors argue that a decrease in forest area will have implications for the local and regional evapotranspiration, and consequently to the overall water regime (Ellison et al., 2012). Forests play an important role in supplying atmospheric moisture that may eventually become precipitation, and at global scales precipitation could decrease significantly if forest continue to be cut. In some areas, forests are associated with water gains by fog interception (Chang et al., 2006). Particularly in coastal and mountain areas, tall vegetation can intercept the equivalent between 5% and 20% of total rainfall (Bruijnzeel, 2004). In a recent experiment in Hawaii, groundwater recharge was 106% of rainfall above-canopy in dense forest cover, as a result of direct interception of cloud water (Brauman et al., 2012).

Structural and functional traits, such as canopy structure and density (Figure 2.1), tree water use and rate of growth, vary among tree species contributing to different water balances in forests. In general, deciduous tree species intercept lower amounts of water from rainfall annually than evergreen species, about 18 % and 31 % of total rainfall, respectively (Barbier et al., 2009). In addition, rapid growing species, such as eucalyptus, are associated with higher water demands, increasing concerns of water availability when plantations are located in areas with prolonged dry periods (Garmendia et al., 2012). This was shown in an experiment in northern Spain, where seven years after the establishment of a eucalypt plantation, the decrease in the water table dropped from about 3 mm/day to 5 mm/day (Rodriguez-Suarez et al., 2011).

Overall, there are positive and negative effects (see Table 2.1) of forests and afforestation on the several processes involved in water quantity (Brauman et al., 2007). The relative importance of these factors, as well as the final balance for water yield, seems to be highly dependent on the specific environmental and social-ecological context of each region (Calder, 2002).

2.2.2.2. Water timing

Forests promote infiltration, consequently inducing groundwater recharge and influencing the hydrological functioning of the watershed (Bosch & Hewlett, 1982). Therefore, the general perception is that forests influence the regulation of seasonal flows, namely reducing peak flows and increasing water on dry flows. However, the way forests regulate seasonal flows is very site specific and dependent on the type of climate, biophysical conditions of the watershed, vegetation cover dynamics and species traits (Calder, 2002). To better understand this regulation process, three factors in forest water balance should be considered: (1) the input of rain; (2) throughfall and infiltration; and (3) evapotranspiration (Figure 2.1).

The effects of rainfall pattern on water infiltration are determined by the amount and frequency of precipitation throughout the year, and by the intensity of the rainfall episodes (Brauman et al., 2007). In some regions of the tropics, rainfall intensity often exceeds 100 mm/hour (Cheng et al., 2002). These extreme episodes influence soil field capacity due to the amount of water that fills the soil empty spaces in a short time (ChapinIII et al., 2002). In addition, the function of water regulation is intrinsically linked to water retention capacity across the watershed, and soil depth determines the amount of water that can be stored in the system (Neary et al., 2009).

After a rainfall episode in a forest, part of the water not evaporated back to the atmosphere is stored by leaves and drips to the ground (throughfall) or runs down stems to the ground (stem flow) (ChapinIII et al., 2002). Thus, trees, understory vegetation and litter dampen and slowly release rainfall to the ground, influencing water infiltration by avoiding surface runoff. In addition, soil hydraulic properties such as conductivity and porosity influence infiltration and storage capacity of each soil (Waring & Running, 2007). Tree root system and soil microorganisms are the major agents of soil porosity and structure (EASAC, 2009; Elmqvist et al., 2010). A meta-analysis of 14 experiments in the tropics showed that, with grass and crops, infiltration ranges between 3-47 mm/h, whereas after forestation it ranges between 6-172 mm/h (Ilstedt et al., 2007).

Finally, the water balance is also influenced by evapotranspiration in forest ecosystems. Canopy evaporation or interception is high in forests and will vary according to the type of tree canopies, radiation amount, temperature and wind conditions (Waring & Running, 2007). Under temperate climate, forest interception ranges from 15-50% of rainfall (Gerrits et al., 2010). On the other hand, water use by trees is a key determinant of water availability, according to canopy leaf area and climate characteristics (Aranda et al., 2012). Evapotranspiration from a forest catchment with eucalyptus could be 40-250 mm higher than from a comparable catchment with grasslands in Australia (Farley et al., 2005). Specifically during the dry period, increasing demands of transpiration will require deep water uptake by plants, and hence a reduction of water flows (Calder, 2002). Forests can, however, compensate this by enhancing water infiltration all over the year, increasing soil water recharge and water storage, with evidences in the tropics (Bruijnzeel, 2004).

The timing of water is also dependent on the seasonality of tree species traits. In temperate forests for instance, deciduous tree species are foliated during summer, when evapotranspiration is higher and precipitation is lower. An experiment with beech species in Luxembourg, revealed that in summer, canopy and forest floor interception is 36% of rainfall, whereas in winter is 26% (Gerrits et al., 2010). In turn, forest management actions can also influence the water balance. In the Mediterranean, an experiment revealed that after 33% reduction of stem basal area by thinning, interception in holm oak decreased from 31% to 21% of total rainfall (Limousin et al., 2008).

It is difficult to generalize the impact of vegetation on seasonal flow regime without considering the type of climate (Calder, 2002). Empirical evidence in the literature reveals that catchments with uniform rainfall throughout the year also exhibit uniform reductions in water flow across seasons. In an experiment in New Zealand, there was approximately 30% reduction of water flow as a result of the establishment of a pine plantation (Brown et al., 2005). On the contrary, catchments with predominant winter rainfall, like semi-arid or Mediterranean regions, show larger reductions in summer flows, since rainfall and evapotranspiration are out of phase (Brown et al., 2005). This is particularly important in water scarce environments, in which the potentially beneficial effects on peak flow reduction by forests are balanced with the negative effects on dry flow reductions (Brauman et al., 2007).

There is wide agreement that the mitigation of water-related hazards, such as floods, is related to the regulation of flows and improved by the presence of forests (Calder & Aylward, 2006). In tropical regions, floods are a well known phenomena and some authors suggest that deforestation is amplifying the risk of flood-related catastrophes (Bradshaw et al., 2007). However, other authors argue that the causes are much more complex and site specific, mainly related to climate change, higher population density and urban infrastructures (van Dijk et al., 2009; Tran et al., 2010b). The growing consensus is that forests may help to mitigate floods from small storms, as forests evaporate more and soils facilitate infiltration, but the effects on strong storms are likely to be insignificant (Calder & Aylward, 2006). Accordingly, studies in the Central Spanish Pyrenees have shown a reduction in the frequency of floods when there is forest cover, even if this cover does not alter significantly the negative effect of extreme rainfalls (Serrano-Muela et al., 2008).

Table 2. 1 - Synthesis of general forests ecohydrology and hydrological services, compared forest to non-forest areas.

Service	Ecohydrological process	Rationale forests-water	Effect on service	Reference
Water supply				
Quantity	Runoff (Water yield)	Results in a reduction of water for discharge	↓	Farley *et al.*, 2005
	Evapotranspiration	High evaporation of intercepted water. Forest transpiration (depending on tree species and region)	↓	Zhang *et al.*, 2001
	Fog and cloud interception	Forest intercept water from fog (mainly in coastal and mountain areas) and clouds (tropical rain forests) promoting gradual water throughfall	↑	Brauman *et al.*, 2012
	Atmospheric moisture	Evapotranspiration from forests contributes to increase atmospheric moisture and to feed precipitation	↑	Ellison *et al.*, 2012
	Infiltration	Forests promote infiltration thereby increasing soil moisture and promoting aquifer recharge	↑	Ilstedt *et al.*, 2007
Timing	Evapotranspiration	Seasonality on the rates of evapotranspiration may reduce water losses in some regions	↑	Brown *et al.*, 2005
	Throughfall	Usually high in forest, promoting infiltration and thereby aquifer recharge	↑	ChapinIII *et al.*, 2002
	Infiltration	Forests promote infiltration and the gradual release of water throughout the year	↑	Calder, 2002
Quality	Surface runoff	Lower under forest cover contributing to reduce surface sediment transport for watercourses	↑	Neary *et al.*, 2009
	Nutrient uptake	Forest organisms use large amounts of nutrients, filtering them and thereby contributing water quality	↑	Pert *et al.*, 2010
Water damage mitigation				
Quantity	Runoff	Reduction is positive for water hazard mitigation e.g. peakflow reduction in regions with very high precipitation rates and steep slopes (but only at the limit of soil retention capacity)	↑	Tran *et al.*, 2010
	Surface runoff	Low, promoting soil stability and reducing erosion by running water	↑	Lin *et al.*, 2008
Timing	Infiltration	High infiltration regulates water flows, minimizing the frequency and the effects of droughts and floods (the latter at the limit of soil retention capacity)	↑	Calder and Aylward, 2006

↑positive effect; ↓negative effect

2.2.2.3. Water quality

The role of forest in determining water quality can be expressed in two main outputs: water with less sediment, and water with fewer nutrients (mainly nitrogen) (Elmqvist et al., 2009). Water with less sediment is directly linked to the process of surface runoff (Figure 2.1). Tree canopies avoid direct rainfall splash on the soil. In addition, the tree root system fixes the soil, consolidating slopes and preventing river siltation (Neary et al., 2009). Therefore, if forests are present, particularly in the tropics, less surface sediment goes into the rivers, and activities such as hydropower production may be performed more efficiently (Hewawasam, 2010). Reductions in sediments can be up to 50 % after forestation, as was shown in an experiment in Taiwan, where sediments drop from about 16 000 t/year under farmland to 6 000 t/year under forests (Lin et al., 2008). However, consideration should be given to the interventions on plantation forests, such as trees establishment, harvesting or bushfires, which can mobilize large amounts of soil sediments (van Dijk & Keenan, 2007; Figueiredo et al., 2011).

Compared to other land cover types, forests generally do not receive nitrogen input, and are indeed, consumers of nutrients (Brauman et al., 2007). Soil organisms are therefore important for the biochemical modification of organic compounds (Elmqvist et al., 2009). Some studies reported the efficiency of riparian forests in removing over 90% of nitrates from groundwater that flows through them (Pert et al., 2010).

It should be noted that trade-offs could arise between forest expansion and nitrogen concentration. When the issue is pollution concentration, forests and the resulting reduction of water in catchment flows may act as a “disservice” of water quality, rather than have a positive effect on trapping pollutants (van Dijk & Keenan, 2007). Concentrations of nutrients are higher in low flows, with harmful consequences for fish survival and for general population water use (Otero et al., 2010).

2.2.3. Indicators for evaluating hydrological services

To support application of the proposed conceptual framework, a set of indicators for the assessment of hydrological services is suggested (Table 2.2). Indicators at different stages of the framework show different levels of information that can be useful for decision makers to adopt good strategies on land management, taking into account the benefits for populations and the trade-offs among types of services (van Oudenhoven et al., 2012). However, indicators are often difficult to generalize, particularly if they are site specific and calibrated to a particular set of environmental characteristics (Layke, 2009; Maes et al., 2011).

Table 2.2 provides examples of indicators suggested in the literature to describe the properties, functions, services and benefits related to the hydrological system. Individually these indicators are not fully adequate to characterize the diversity and complexity of hydrological services provision, e.g. supply and demand of services. The idea is therefore to use a set of complementary indicators that can jointly provide a coherent view of hydrological services, under the conceptual framework for hydrological services provision by forests (Figure 2.1). Most of the indicators in Table 2.2 can be spatially explicit at several scales. The quantification can be made regarding all ecosystems, but here the role of forests in controlling hydrological processes was highlighted.

Table 2. 2 – Some examples of indicators for hydrological services evaluation, organized according to the conceptual framework

	Role of forests	Indicator, units or range	References
Properties			
Evapotranspiration (ET)	Evapotranspiration is large under forests and determines the amount of water loss to the atmosphere	Evapotranspiration (mm/yr)	Layke (2009)
Canopy structure and density	Tree canopies intersect rainfall as a function of leaf area preventing soil from erosion by water	% of soil covered by forests and semi-natural ecosystems	Maes et al. (2011)
Function (potential use)			
Capacity to store water	Forests soils have high capacity to store water and releasing it gradually	Annual water flow (mm)	Maes et al. (2011)
Capacity to trap sediments	Under forest cover surface runoff is low reducing soil erosion	Area affected by erosion (km^2)	Layke (2009)
Service (actual use)			
Water supply	Although forests contribute to lose water through ET, they promote infiltration making water available seasonally	Available water resource (m^3)	Layke (2009)
Water damage mitigation	Forest cover, particularly the root system, fixes soil on slopes and reduces water damage	Soil loss estimates as a function of forest cover (t/ha.yr)	Maes et al. (2011)
Benefit			
Water supply	Forests contribute to improve water quality	Water consumption by sector (m^3)	Layke (2009)
Hydropower generation	Role of forest on the regulation of water flows and soil retention	Hydropower potential (megawatts)	Layke (2009)

Underlying the provision of hydrological services is the water cycle, which by nature is a complex set of interrelated processes, and therefore difficult to quantify and model. According to Vigerstol & Aukema (2011), tools for modelling hydrological services can be divided into traditional hydrological tools and new ecosystem service oriented tools. Traditional hydrological tools are based on robust hydrological modelling at the watershed or basin scales, such as SWAT (Soil and Water Assessment Tool) (Arnold & Fohrer, 2005). Ecosystem service oriented tools are based on ecosystems service indicators and models across larger areas such as InVest (Integrated Valuation of Ecosystem Services and Trade-offs) (Nelson et al., 2009). The latter are more accessible for non-experts and provide a more integrative picture of ecosystem services considering both the biophysical and social part, whereas hydrological modelling tools usually require extensive data collection and focus only on the biophysical part (Vigerstol & Aukema, 2011). The incorporation of more biophysical models with validation methods, such as SWAT, for ecosystem services quantification is making progress, as it was presented in a watershed in the EUA (Logsdon & Chaubey, 2013).

2.2.4. Social-ecological perspective for hydrological services

After addressing the ecological interactions between forests and water, the understanding of hydrological services provided by forests will only be adequately framed if considering it in the context of social-ecological systems and their dynamics (Haines-Young & Potschin, 2010). The FESP (Framework for Ecosystem Service Provision) based on DPSIR (Drivers, Pressures, State, Impacts and Responses) (Rounsevell et al., 2010), can also be applied to specifically assess the provision of hydrological services by forests (Figure 2.2). External drivers and internal pressures are threatening hydrological systems, concerning both the biophysical and the societal elements. They modify the processes and functions behind the provision of hydrological services, changing the system state and creating impacts that require effective responses.

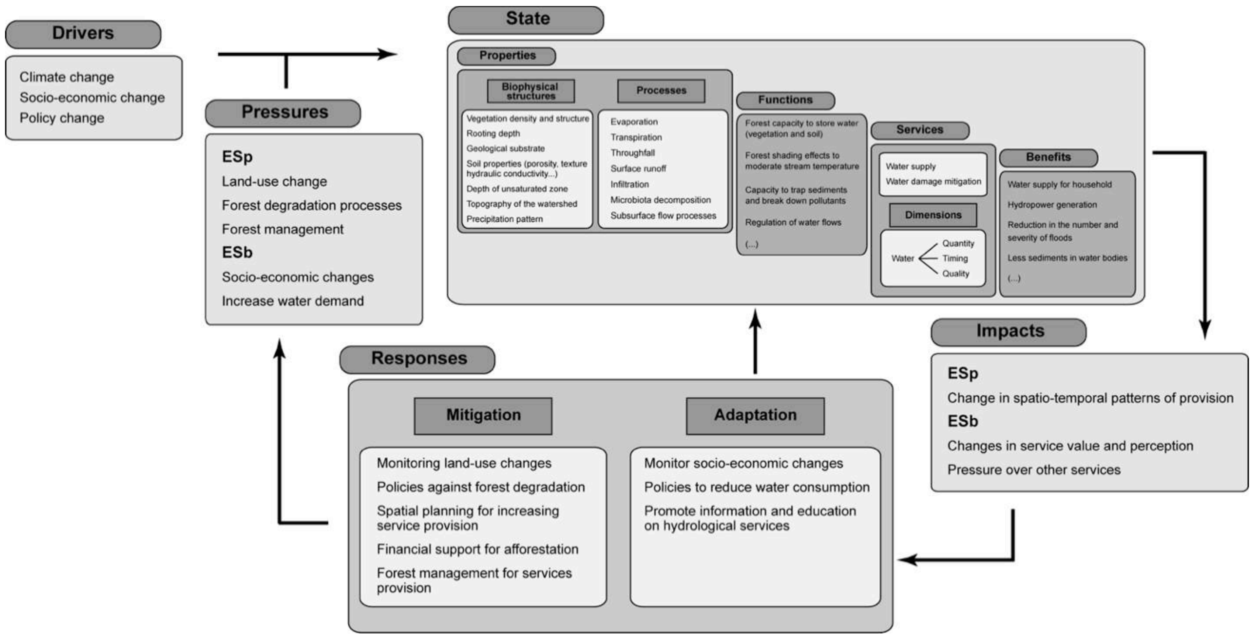

Figure 2. 2 – The Framework for Ecosystem Service Provision (FESP) applied to hydrological services provided by forests. DPSIR (Drivers, Pressures, State, Impacts and Responses). ESp – ecosystem services providers. ESb – ecosystem services beneficiaries. Modified from Rounsevell et al. (2010).

In this framework, external drivers of change influence directly the pressures and indirectly the state on ecosystem service provision (Rounsevell et al., 2010). Such drivers may include climate change, expressed as changes in precipitation amount and seasonality, which will influence water supply. Particular factors for ecosystem service providers (ESp) and beneficiaries (ESb) were identified both for pressures and impacts (Figure 2.2). ESp represents the supply and ESb the demand. From the supply point of view, the key pressures on hydrological services provision by forests are: (1) land-use change, e.g. land abandonment will promote forest growth and expansion; (2) forest degradation processes, such as wildfires and invasive species; and (3) forest landscape management, including changes in forest practices. From the demand perspective: (4) socio-economic changes, such as unemployment and (5) an increase of water demand, will require measures to improve the provision.

To represent the state of the system, the framework illustrated in Figure 2.1 was used, since it reflects the definition and quantification of forest attributes important for the supply of hydrological services, as well as the demand from society at a given moment. Changes of state will imply negative impacts, such as shifts in the spatiotemporal patterns of service provision that will influence the interactions between supply and demand of the service. Demand will change the value of the service or can create pressures over other services.

Responses will directly influence system state with adaptation measures, such as policies to reduce water consumption or promote education about hydrological services. Mitigation measures acting directly on pressures may include financial support to afforestation and policies against forest degradation.

2.3. Illustrating the framework at a regional scale

2.3.1. Environmental and social-ecological setting of northern Portugal

Northern Portugal is a heterogeneous region that corresponds approximately to one fourth of the country (Figure 2.3a). Throughout decades the eastern and mountainous parts of this region have suffered from depopulation (Lomba et al., 2013). Consequently, land abandonment is leading to natural forest and scrubland regeneration. Nonetheless, the larger forest areas are still located on the western part, where the stronger Atlantic climatic influence favours the development and resilience of forest ecosystems (Figure 2.3d).

A key feature of northern Portugal is the sharp difference between the climate conditions of the west and east areas, as it can be seen from the precipitation climatic gradient (Figure 2.3b). According to Köppen climatic classification, both areas have Mediterranean temperate climate with dry summer, but on the east side the hot and dry summers contrast with temperate summers typical of the west. Lower temperatures and higher annual precipitation characterize the Atlantic west side (Figure 2.3b). Due to the barrier effect promoted by the north-south orientation of the Alvão-Marão mountains range (Figure 2.3), this maritime influence hardly reaches the east part of the region, which is dryer and more continental. Those mountains are parallel to the coast, receiving and condensing the humid air masses from the Atlantic Ocean, impoverishing them in humidity to further continue east (Mesquita & Sousa, 2009). According to precipitation records, annual rainfall in the northwest mountains can reach up to 3 000 mm/year in wet years. Conversely, precipitation records in the east side are markedly lower, and in some areas annual precipitation does not reach 400 mm (IM-AEM, 2011).

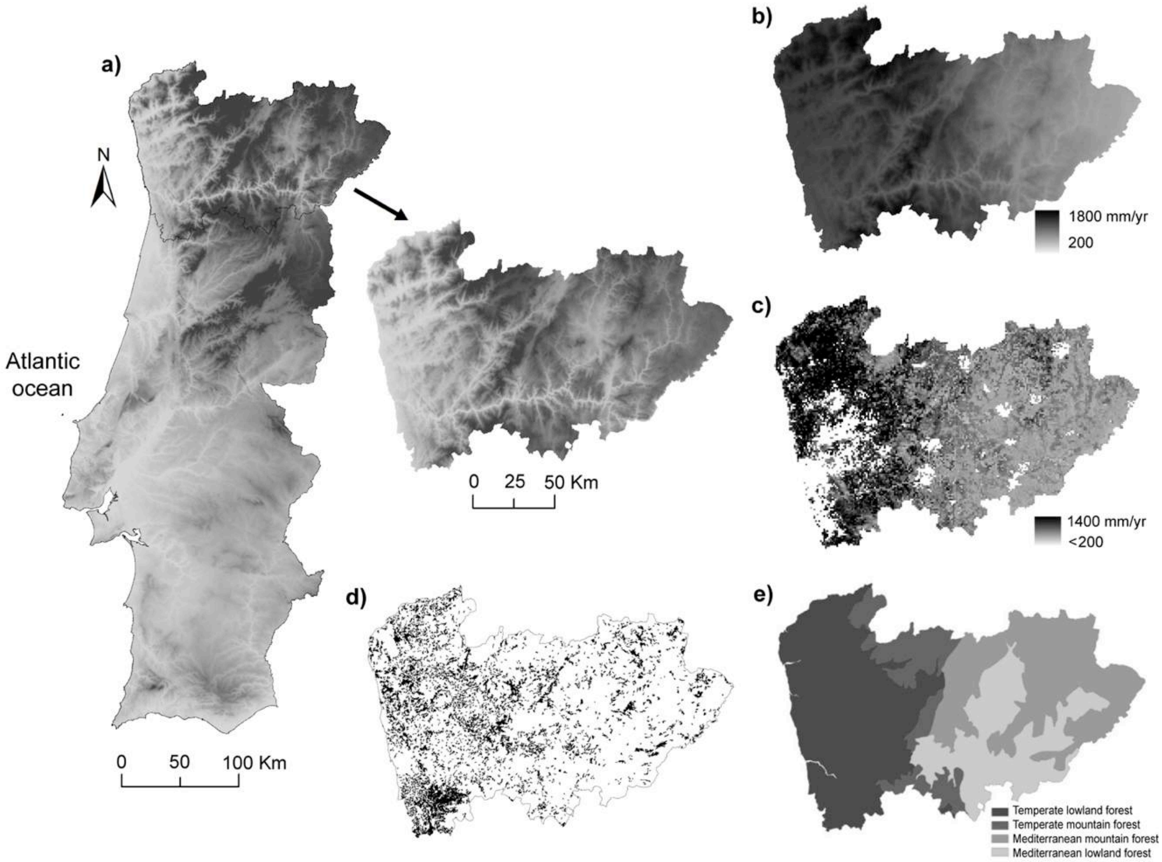

Figure 2. 3 – The study area. Indicators and sources: a) Location - Digital elevation model (SRTM – 90 m resolution); b) Mean annual precipitation (mm/yr, 250 m^2 pixel resolution) from Worldclim database, 1950-2000 (Worldclim, 2010); c) Mean annual evapotranspiration (mm/yr, 1km^2 pixel resolution) from MODIS, 2000-2010 (MODIS, 2010); d) Forest distribution (evergreen, broadleaved and mixed) – from CORINE Land Cover 2006 (EEA, 2006); and e) Simplified map of potential native forests - modified from Costa et al. (1998).

The potential distribution of native forest types in the region is mainly controlled by climate (Figure 2.3e). The potential forests in the west side are temperate deciduous, with common oak (*Quercus robur* L*.)* across the whole area and iberian birch (*Betula celtiberica* Rothm. & Vasc.) in mountain areas. Mediterranean forests potentially dominate in the east, with pyrenean oak (*Quercus pyrenaica* Willd.) in mountain areas and Portuguese holm oak (*Quercus rotundifolia* Lam.), cork oak (*Quercus suber L.)* and juniper (Juniperus oxycedrus L.) in lower altitudes (Figure 2.3d). Forests in the east side are composed of evergreen sclerophyllous trees and shrubs, which have evolved resistance mechanisms to respond to dry conditions and exhibit great resistance to fluctuations in rainfall and water availability. For centuries, most of these forests have been cut or heavily managed, so the predominant forest types in the region nowadays are forestry stands mainly of pines (*Pinus pinaster* Aiton) and eucalypts (*Eucalyptus globulus* Labill.), perfectly adapted to the climatic conditions of large parts of the region.

2.3.2. The framework applied to water supply and water damage mitigation

In order to illustrate the applicability of the conceptual framework (see Figure 2.1), some of the indicators listed in Table 2.2 were modelled and represented with maps to document features of the water supply service (quantity), and of the water damage mitigation service (soil erosion control). Northern Portugal was chosen to illustrate the framework, because of its environmental and socio-economic heterogeneity, and due to the spatial/temporal availability of data to inform on indicators for the several stages of the framework (see Table 2.3 for dataset description).

Table 2. 3 - Datasets and sources used to build the maps from Figure 4.4.

	Hydrological Service			
	Water Supply (Water quantity)		**Water damage mitigation** (Soil erosion control)	
Scale of analysis	Calculated at 1km grid Aggregated at the municipality level		Calculated at 1km grid Aggregated at Water Framework Directive (WFD) sub-basin level	
Equation	$R \approx P - ET$ (modified rainfall partioning equation ($P \approx ET + R$))		$A = R * K * LS * C$ (RUSLE equation, without P factor for land management practices. See table 1 in Appendices for K and C factors description	
Datasets, sources and scale resolution	ET Evapotrans-piration (Fig. 4a)	MOD – 16 evapotranspiration product from MODIS sensor, annual average from 2000-2010, $1km^2$ pixel resolution http://modis.gsfc.nasa.gov/	R – rainfall erosivity	Annual average isoerosivity lines, 25.4 mm threshold, from the Water Atlas of Portugal, SNIRH (National information system for water resources) (http://geo.snirh.pt/AtlasAgua/)
	P Precipitation (Fig. 3b)	Wordclim database 1950-2000, $1km^2$ pixel resolution http://www.worldclim.org	K - Soil erodibility	Soil Map of Portugal, SROA, 1971, 100m, from Environmental Atlas of Portugal (http://sniamb.apambiente.pt/webatlas/)
	Water abstracted (Fig. 4d)	Mean annual values, by municipality, between 2006 and 2008 (urban uses) From Statistics Portugal, INE http://www.ine.pt/	LS - Slope length and steepness	DEM – from GDEM (Global Digital Elevation Model), 30m, Aster instrument, Terra satellite, (http://asterweb.jpl.nasa.gov/gdem.asp)
			C - Land cover; Forest cover (Fig. 4e)	Corine Land Cover, 2006, 100m http://www.eea.europa.eu/
			Dams and rivers (Fig. 4h)	Water Atlas of Portugal, SNIRH (http://geo.snirh.pt/AtlasAgua/)

The role of forests was not directly quantified due to model limitations, but it was spatial-explicitly illustrated, highlighting the areas where the service is most needed, according to the indicators included in the framework (Figure 2.1). For water quantity, the modified water balance equation ($P \approx ET + R$), which makes the partioning of rainfall between runoff and evapotranspiration at the surface level, was used (ChapinIII et al., 2002). According to this equation, water inputs from precipitation (P) are more or less equal to the sum of the water loss to the atmosphere through evapotranspiration (ET) and of the water that stays in the system, or runoff (R) here defined as water surplus (Figure 2.4). Since this regional illustration does not consider sub-surface water and groundwater water modelling, the benefits of forests for improving infiltration cannot directly be presented. This would demand using data at more detailed spatial scales (watershed), dynamically with hydrological modelling, to understand the role of forest and land-cover change on the provision of hydrological services. Here, forests were presented as high contributors for evapotranspiration, which may influence the water quantity service, although the order of magnitude is very site specific. Recent studies performed in northern Portuguese watersheds have found an apparent small impact of mass afforestation on river discharge, when compared to the magnitudes reported in the literature (Hawtree et al., 2014). This small effect of forests, probably results from a difference in water use potential of vegetation, given that precipitation and evapotranspiration in Mediterranean type of climates are out of phase. Definitive conclusions on the effects of forests on the annual water quantity are not possible at this stage. The framework however, provides a good picture of the spatial distribution of rainfall partitioning in the region as well as of the spatial relations between water, forests and the societal demands for hydrological services provision. To illustrate a more evident positive contribution of forests for hydrological services, soil erosion control was modelled using the Revised Universal Soil Loss Equation (RUSLE) (A = R * K * LS * C * P) (Renard et al., 1997). Table 2.3 and 2.4 further details the equation factors and model steps. Here, special attention is given for C factor (Figure 2.4f), because it describes the effect of land cover on soil erosion (see Appendix A – Table A.1). For example, evergreen forests, shrubs and herbaceous vegetation are known to have an important contribution for soil erosion control, receiving the lowest values for C factor (Pimenta, 1998).

Table 2. 4 – Methods used in each step of the framework illustration

	Property	Function	Service	Benefit
Water supply (quantity)	Representation of MOD-16 evapotranspiration product (improved algorithm, based on the Pennan-Monteith equation, computed from MODIS land cover, MODIS-15 LAI/FPAR, and global surface meteorology from GMAO). Map units were converted from mm to m^3. Data was aggregated at municipality level, using zonal statistics (average value). Previously, all the municipalities with less than 50% of their area (i.e. pixel number) holding information in the original MODIS dataset were excluded.	R = P – ET Water surplus (R), the water that stays in the system after rainfall, is more or less equal to the mean annual precipitation (Figure 2.3b) from Wordclim database 1950-2000, less evapotranspiration (Figure 2.4a). Data was aggregated at the municipality level, using the same method described in evapotranspiration map.	Water availability corresponds to the ratio water surplus (Figure 2.4b) and water abstracted by municipality (Figure 2.4d).	Water abstracted is based on average annual values (2006 – 2008) to fill data gaps, at municipality level (INE, 2007). To approximate the water abstracted values, which corresponds mainly to urban use, to the estimates of the total water abstracted, we multiply these values by 20. We based this value on the premise that in Portugal about 87% of water is used for agriculture, 8% for industry, and only 5% for urban consumption (INSAAR, 2011).
Water damage mitigation (soil erosion control)	Forest cover from CORINE land cover map (broadleaved, evergreen and mixed forest). Aggregated at the WFD (Water Framework Directive) sub-basin scale using zonal statistics, sum of the area.	C factor used to compute RUSLE equation, according to Pimenta, 1998 and Jones *et al*, 2011.	A = R * K * LS * C Factors computed at 250m^2 pixel and aggregated at sub-basin scale, average values. P factor for land management practices was not considered because data was not available. LS factor calculation, was based on Jones *et al*. 2011 and Helena Mitosova webpage. (http://skagit.meas.ncsu.edu). Length - √(l/22.1) 0.6 Steepness - [(sin(slope)]^2 0.09)/ 0.9, 1.4	Represents the basins with dams and upstream influence according to the soil erosion risk map (Figure 2.4g).

To illustrate the framework at a regional scale for northern Portugal, we used municipalities for the water supply service and the sub-basins from the WFD (Water Framework Directive) for the erosion control, as mapping units. This is in accordance with the national water management units, in which municipalities are responsible for the distribution of water, and the National Water Institute is responsible for monitoring soil erosion and water quality. The spatial analysis was conducted on the ArcGIS 10 ESRI software. Information for maps 2.4a, b, f and g were available at finer spatial scales (1km^2 resolution), but for reasons of consistency between the maps, all information was presented at the same spatial scale (municipalities or sub-basins) (Figure 2.4).

2.4. Discussion

Figure 2.4 aims to illustrate the utility of the framework (described before in Figure 2.1) for the regional assessment of water-related ecosystem services, using a sequential cartography of different indicators. In the context of a real assessment of hydrological services to support spatial planning or land management, these indicators should be estimated using dynamic, robust, spatially and temporally explicit, modelling frameworks (e.g. SWAT (Arnold et al., 1998)), in order to capture the complexity of eco-hydrological processes involved as well as the interactions among them (Vigerstol & Aukema, 2011). Thus, Figure 2.4 is only intended to document the coarse spatial distribution of water quantity and soil erosion control in northern Portugal, as an illustration of how both the supply and demand sides of the provision of hydrological services can be considered in a common framework.

Concerning the water supply service, features for evapotranspiration (Figure 2.3c) attempts higher values in the western part of northern Portugal, where climatic conditions are favourable for higher potential evapotranspiration. This determines lower water surplus values (Figure 2.4b), even if the precipitation rates are relatively high (Figure 2.3b). At the municipality level (Figure 2.4a), the pattern of evapotranspiration and water surplus is area dependent, meaning that larger municipalities will hold the highest levels of evapotranspiration and water surplus. The lowest values for both maps are mainly concentrated in the west part, where high evapotranspiration and small municipalities prevail. Water surplus (Figure 2.4b) attains high values in mountain areas, where the highest rainfall values coincide with the lowest regional evapotranspiration rates (Figure 2.3c). At high altitudes, grasslands, shrubs and rock outcrops mostly replace forests. Those areas may therefore contribute to retain water that could be transferred gradually for water supply downstream, compensating for the high rates of forest evapotranspiration in western lowlands. The service indicator for water availability illustrates how water supply provisioning areas are spatially related to those where higher water abstraction occurs. This is important for a regional analysis of supply and demand across municipalities. The water availability ratio (Figure 2.4c) is higher in municipalities where water surplus is high (Figure 2.4b) and water abstracted is low (Figure 2.4d). Lower ratios are located in the west part where the demand for water is higher (more densely populated municipalities) and water supply (water surplus) is lower due to high evapotranspiration rates. In the east part, the ratios of water availability are higher due to lower demand for water as well as lower rainfall values. In all municipalities analysed the supply of water after rainfall partitioning between evapotranspiration and runoff (water surplus) sufficed the demand (water abstracted), translating into values of the water availability ratio higher than 1 (Figure 2.4c). This would suggest that precipitation inputs minus evapotranspiration losses are enough to satisfy people's needs at the municipality level, considering current domestic, industrial and agricultural water consumption. Considering adequate data is available, this modelling exercise could be replicated with regular time intervals, in order to monitor both water supply and water demand.

For water damage mitigation (soil erosion), the service indicator (Figure 2.4g) refers to the potential soil erosion, considering, among others, the C factor of the RUSLE (Figure 2.4f) that signals forest, herbaceous vegetation and shrubs as favourable covers (i.e., with low C factor). The sub-basins with the highest soil erosion risk are located in the west part of the region, mainly related to rainfall erosivity, length/steepness of slopes and prevailing high C factors. In the southwest part, the lower levels of soil erosion risk may be related to higher forest cover and lower rainfall erosivity. In this case, the rationale for water damage mitigation (soil erosion) service follows a slightly modified supply and demand exercise, when compared to water supply exercise. The reason is the lack of available data for the benefit indicator (e.g. amount of sediments collected from dams or avoided maintenance costs). As a proxy indicator, we chose to distinguish the sub-basins with water dams according to their soil erosion risk. Following an ecosystem service rationale, a reduction of soil loss could be achieved if some forestation efforts may be implemented, but detailed studies at watershed level are recommended. Besides, forestation efforts may indirectly raise soil erosion risk due to high forest fire susceptibility and intensive management operations in the new forest plantations. Spontaneous forest regeneration through succession could thus be a more favourable management option (Jones et al., 2011).

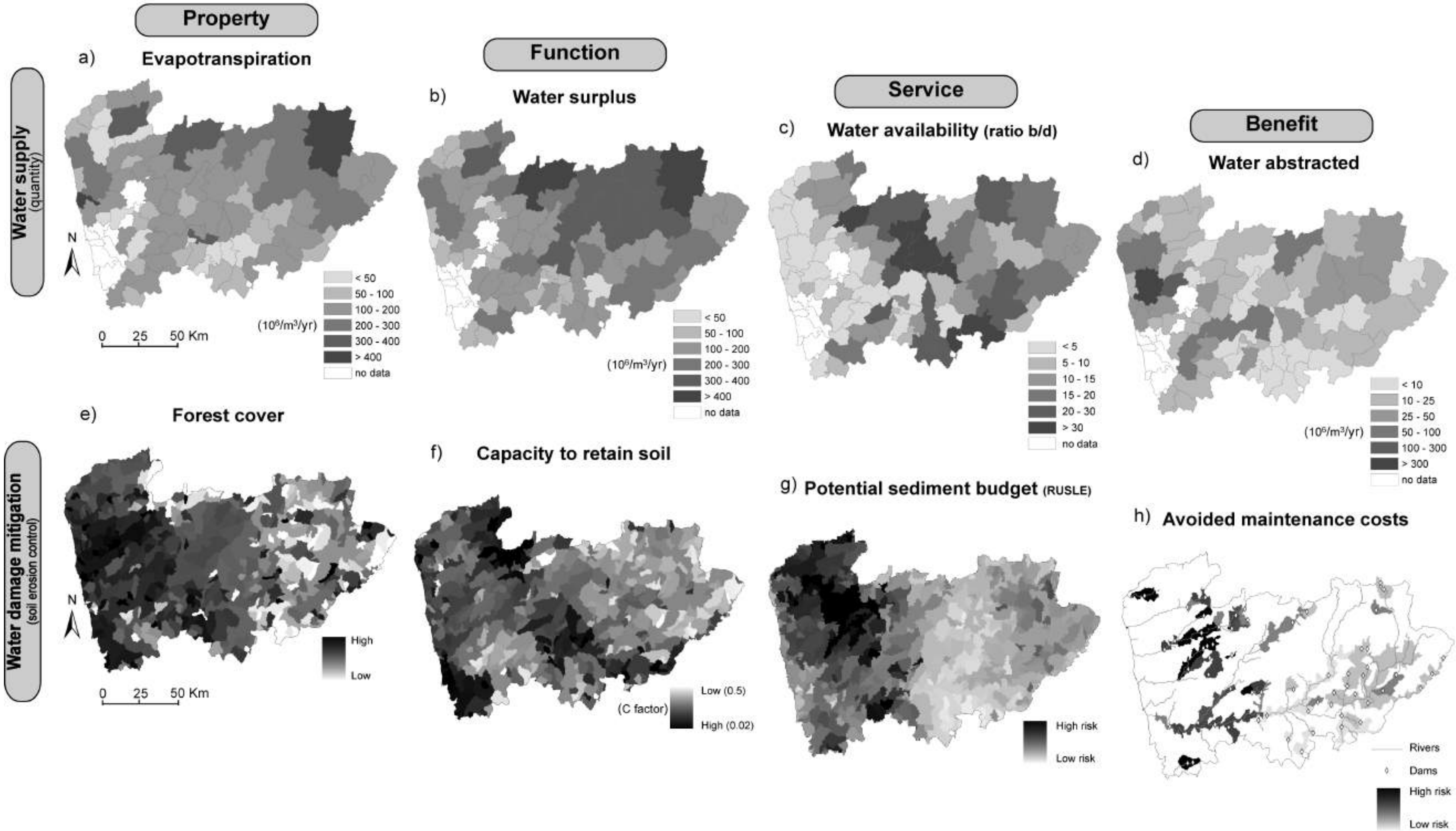

Figure 2. 4 - Illustration of the conceptual framework of hydrological services provided by forests using two examples: water supply (quantity) at the municipality level, and water damage mitigation (soil erosion control) at the sub-basin level. Indicators, sources and methods (see Table 2.3 and 2.4). a) Evapotranspiration varies according to different vegetation cover as a function of precipitation, solar radiation and temperature, therefore is an indirect indicator of forest and water functioning; b) Water surplus (runoff) reflects the capacity of the system to potentially provide water; c) Water availability reflects the ration between potential available water and the estimation of water use; d) Water abstracted for urban uses and estimated for agricultural and industrial uses; e) Forest cover represents the total forest area in each sub-basin; f) Capacity to retain soil, according to C factor values for land cover related to soil erosion (Pimenta, 1998); g) Potential sediment budget, represents the RUSLE map for potential soil erosion; h) avoided maintenance costs, represents the sub-basins with dams where forests can improve the service of soil erosion control.

Considering the forecasted changes in climatic conditions (e.g. Nunes et al., 2008), some general guidelines for the development of effective rural policies in northern Portugal can be pointed out, from a forest management perspective and considering hydrological services. However, when formulating those guidelines we must be aware of the limitations of the static modelling approach presented here, which limits detailed considerations on forests-water relations. An increase of forest area, especially in the drier east part of the region, may have a negative effect on water flows, especially if this expansion is achieved through more water-demanding, fast-growing tree species (e.g. eucalypts). However, based on recent studies, the magnitudes of change are expected to be low (Hawtree et al., 2014). In all cases, trade-offs between forest growth and water yield should be considered in any dry environment (e.g. the Mediterranean) where precipitation does not largely exceed evapotranspiration, in order to avoid undesired effects (Bredemeier, 2011). On the other hand, demand for water is higher in the humid west part, requiring more water supply than in the east part. Here, forests may play different roles in mountains and lowlands, as described above, therefore more detailed studies at the watershed level are recommended to support forestation plans and forest management practices that optimize water supply. Throughout the Mediterranean, marginal farmland abandonment is leading to increasing forest and shrub expansion, which may partially explain the observed decline in water resources and reductions in soil erosion (García-Ruiz & Lana-Renault, 2011). The increase of forest area might have positive impacts on soil erosion control in both parts of the region.

The utility of the final outputs resulting from the application of this framework will always be dependent on the quality of the input data. It should also be noted that northern Portugal is presented as a specific case of high heterogeneity in the spatial distribution of climatic conditions and vegetation attributes. The outcomes of applying the framework to other regions will most likely be different, especially if environmental conditions and its spatial heterogeneity are distinct. We acknowledge that the approach for some indicators in the illustration may be somewhat simplistic, since they are constrained by data availability. Nonetheless, the illustration provides a general picture of how the framework can be applied at a regional scale and for various services. To support ecosystem management, any indicator of the framework can be adapted using the four steps to analyse the provision (properties and function) and the use/demand (service and benefit) in a sequential way. A special attention should be given to the service indicator, which materializes the connection between the provision and demand.

The added value of this novel framework is thus that: (1) it provides a comprehensive and structured basis for modelling/mapping relevant ecosystem features in a sequential way; (2) it is flexible and allows using different indicators at various spatial and temporal scales; (3) linked to a dynamic model, it can be used to monitor hydrological patterns through time and across space; and 4) it facilitates gaining an in-depth understanding of both the physical and social features involved in hydrological service provision as part of complex social-ecological systems. Moreover, focusing on the types of ecosystem services that are particularly relevant for each type of ecosystems (in our case, hydrological services of forests) is an important step to better understand the particular ecological and social interactions in the provision of ecosystem services to improve land management options (van Oudenhoven et al., 2012; Villamagna et al., 2013). The advantages of doing so extend to the assessment of urban forest ecosystem services and indicators to inform urban planning (Dobbs et al., 2011). Our framework can be used in support of strategic land management, particularly regarding forest management plans, but also territorial spatial planning across scales.

2.5. Conclusions

The conceptual framework developed and illustrated in this study supports the development of methods and the selection of indicators for analysing hydrological services at regional scales. It can be used for understanding the interactions between forests, water supply and water damage mitigation, in the absence or presence of forests. Additionally, the use of spatially explicit indicators is useful to make the new conceptual framework a more operational tool to support assessment, planning and technical decision. The water supply and water damage mitigation services were illustrated at a regional scale for northern Portugal, by mapping the spatial distribution of the service under Mediterranean and Atlantic climate conditions. With available data, it can likewise be applied in other regions to assess hydrological services as well as be replicated through time to trace patterns of change. Our findings suggested that a combination of indicators related to system properties, functions, services and benefits is an effective way of analysing the provision and demand of hydrological services as a whole. Our framework can be used as a basis for modelling and mapping the complex relations between land cover, ecosystem management and the different aspects of the hydrological service. This is important to improve land planning and management initiatives, such as forestation plans, adapting them to the biophysical conditions of each region and to the roles played by ecosystems in their several biophysical and socio-economic settings.

Acknowledgments

This study was financially supported by FCT (Portuguese Science Foundation) through Ph.D grant SFRH/BD/66260/2009 to C. Carvalho-Santos. J. Honrado received financial support from Programa Operacional Fatores de Competitividade (COMPETE/FEDER) and the Portuguese Government / Fundação para a Ciência e a Tecnologia (FCT), through Project Grant PTDC/AAG-MAA/4539/2012 (“IND_CHANGE”). The authors would like to thank Isabel Poças (University of Porto) for her precious help on remote sensing images. Also thank Rik Leemans (ESA, Wageningen University) for his comments to improve the manuscript.

Chapter 3

Evaluation of hydrological ecosystem services through remote sensing

Abstract

Ecosystems provide hydrological services, namely water supply and water damage mitigation, essential for human well-being. Concerns over water problems and hydrological services provision have been increasing in the last decades, with special emphasis for water scarcity. For an effective water management and planning, hydrological services should be quantified, mapped and monitored. Remote sensing observations, especially satellite-based products, offer reliable, relative low-cost, spatially explicit and near-real time data. Therefore, the use of satellite observations is crucial to support assessments of hydrological services. In this context, it is necessary to be aware of the available satellite products, as well as of their characteristics in order to apply them adequately in water management. The aim of this article is to present an overview of satellite products that can be used to evaluate and monitor hydrological services provision. We start with a conceptualization of hydrological services followed by a description of the relevant elements of the hydrological cycle. Then, we examine the characteristics of the most relevant sensors and satellites used to evaluate and monitor those elements of the water cycle, and we address the use of remote sensing in hydrological modelling. We conclude with some perspectives on the use of remote sensing to support hydrological services evaluation. We based our survey on literature review and information from official websites. The assessment of water supply and water damage mitigation services can strongly benefit from the use of satellite-based products, contributing to improve the understanding of the processes and functions behind their provision, on a spatially explicit and near-real time basis.

Keywords: Hydrological modelling; Hydrological services; Satellite observations; Water cycle.

Based on: Carvalho-Santos C., Marcos B., Espinha Marques J., Alcaraz-Segura D., Hein L., Pradinho Honrado H. (2013) Evaluation of hydrological ecosystem services through remote sensing. In Alcaraz Segura D, Di Bella C M; Straschnoy J V (eds), Earth Observation of Ecosystem Services, CRC Press Taylors and Francis group, Boca Raton, pp. 219-249.

3.1. Society and hydrological services

Water plays an essential role in the functioning of ecosystems, underpinning biochemical cycles, supporting living organisms and their growth, and creating aquatic habitats on Earth (ChapinIII et al., 2002). In addition, humans and society rely on ecosystems to provide hydrological services and the resulting benefits (MA, 2003). Two major types of hydrological services (Figure 3.1) can be identified according to the benefits they generate: (i) water supply, which includes water for household, irrigation and industry, hydropower generation, freshwater products, transportation, recreational and spiritual benefits; and (ii) water damage mitigation, which includes the reduction in the number and severity of floods, decrease in soil erosion and sediment deposition, and mitigation of landslides (Brauman et al., 2007). Both types of services may be evaluated according to three dimensions: (i) quantity (i.e. total amount of water), (ii) timing (i.e. seasonal distribution of the water) and (iii) quality (related to removal and breakdown of pollutants and trapping of sediments) (Brauman et al., 2007; Elmqvist et al., 2009).

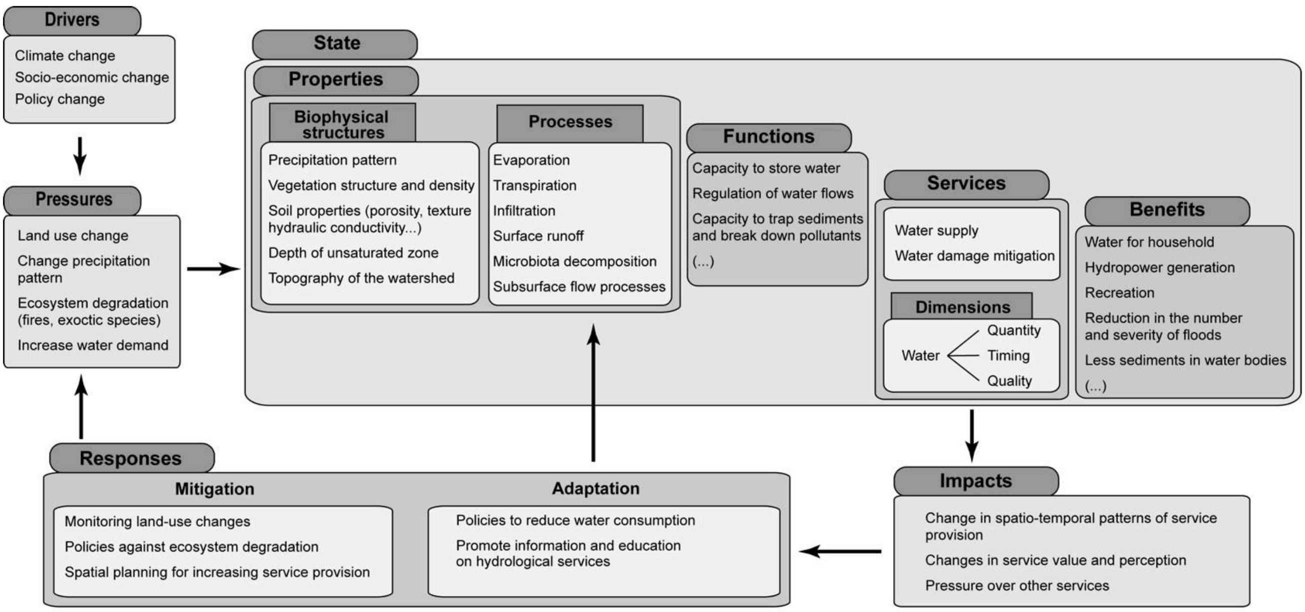

Figure 3. 1 - Framework for the provision of hydrological services, in the context of social–ecological systems. Based on Rounsevell, M. D. A., et al., (2010) and Haines-Young, R., and M. Potschin (2010).

The provision of hydrological services depends on the biophysical structures and processes involving water in ecosystems (Figure 3.1). The rate of ecosystem functioning determines the capacity to deliver a potential service for people (Haines-Young & Potschin, 2010). The intrinsic capacity to provide services exists on nature independently of human options, in the form of ecosystem functions, and services are only materialized when people use or feel the benefits of those functions (Fisher et al., 2009). From one service, multiple benefits can be generated that translate a welfare gain, subject of economic, ecological and social valuation (Ansink et al., 2008; de Groot et al., 2010b). For instance, the amount of water infiltrated will recharge groundwater reservoirs, increasing water storage capacity (properties and functions; Figure 3.1). Once people use this water, the water supply service is translated into economic benefits, such as water being available for household consumption.

Concerns over water problems have been increasing in the last decades, with special emphasis for water scarcity in arid and semi-arid regions (van Beek et al., 2011). Water availability is a function of the biophysical conditions of each region, and the implications of reduced loss of hydrological services tend to be exacerbated in a context of climate change (Brauman et al., 2007). External drivers of ecological change such as climatic, socio-economic and political changes may affect the provision of hydrological services (Figure 11.1). These drivers may influence internal pressures that are directly influencing the state of ecosystems, such as land-use change or increase in water demand (Rounsevell et al., 2010). Those pressures will impact the provision of hydrological services and ultimately affect the corresponding benefits. However, not only supply, but also demand of water must be considered for an integrated water evaluation and planning (Roo et al., 2012). Therefore, responses from both governments and society are needed. For adaptation, policies to reduce water consumption are very important as a response to water overuse. For mitigation, monitoring the internal pressures, such as land use change or precipitation pattern, will help in the design of responses that maintain the integrity of hydrological services (Figure 3.1).

In the face of increasing pressure on water resources and stress on ecosystems regulating water flows, sustainable water management is critical. This is illustrated by the report from UN-Water for Rio+20, which stated that the success of “green economy” depends on the sustainable management of water resources, provisioning of water supply and adequate sanitation services (UN, 2011). Su et al. (2012) recommended to promote the sharing of scientific knowledge and to provide capacity building and transfer of technology on the water cycle among countries, which includes the use of remote sensing and specially the use of satellite technologies, to improve water resource management. Hence, the use of remote sensing is crucial in supporting water management, in particular through allowing assessment and monitoring of the elements of the water balance and of the condition of ecosystems providing hydrological services, over space and time (Wagner et al., 2009).

The aim of this chapter is to present an overview of how remote sensing can be used to support sustainable water management. In particular, we examine how remote sensing, specially satellite techniques, can be used to analyse and monitor ecosystem components relevant to the water cycle and the provision of hydrological services. And also, how remote sensing can support hydrological modelling. We base our analysis on a review of remote sensing and hydrological literature as well as our experience with the spatial modelling of hydrological services.

3.2. Hydrological services and the water cycle

The Millennium Ecosystem Assessment framework highlighted the close relationship between human well-being and water circulation in natural systems (MA, 2003). The best way to illustrate this link is by means of the water cycle conceptual model, which reports to the continuous water movement throughout the Earth's reservoirs, namely oceans, ice caps, glaciers, aquifers, rivers, lakes, soil and atmosphere (Fetter, 2001). The main physical processes involved in the water cycle are: evaporation, evapotranspiration, condensation, precipitation, infiltration, overland flow, interflow, runoff, and groundwater flow (Fitts, 2002).

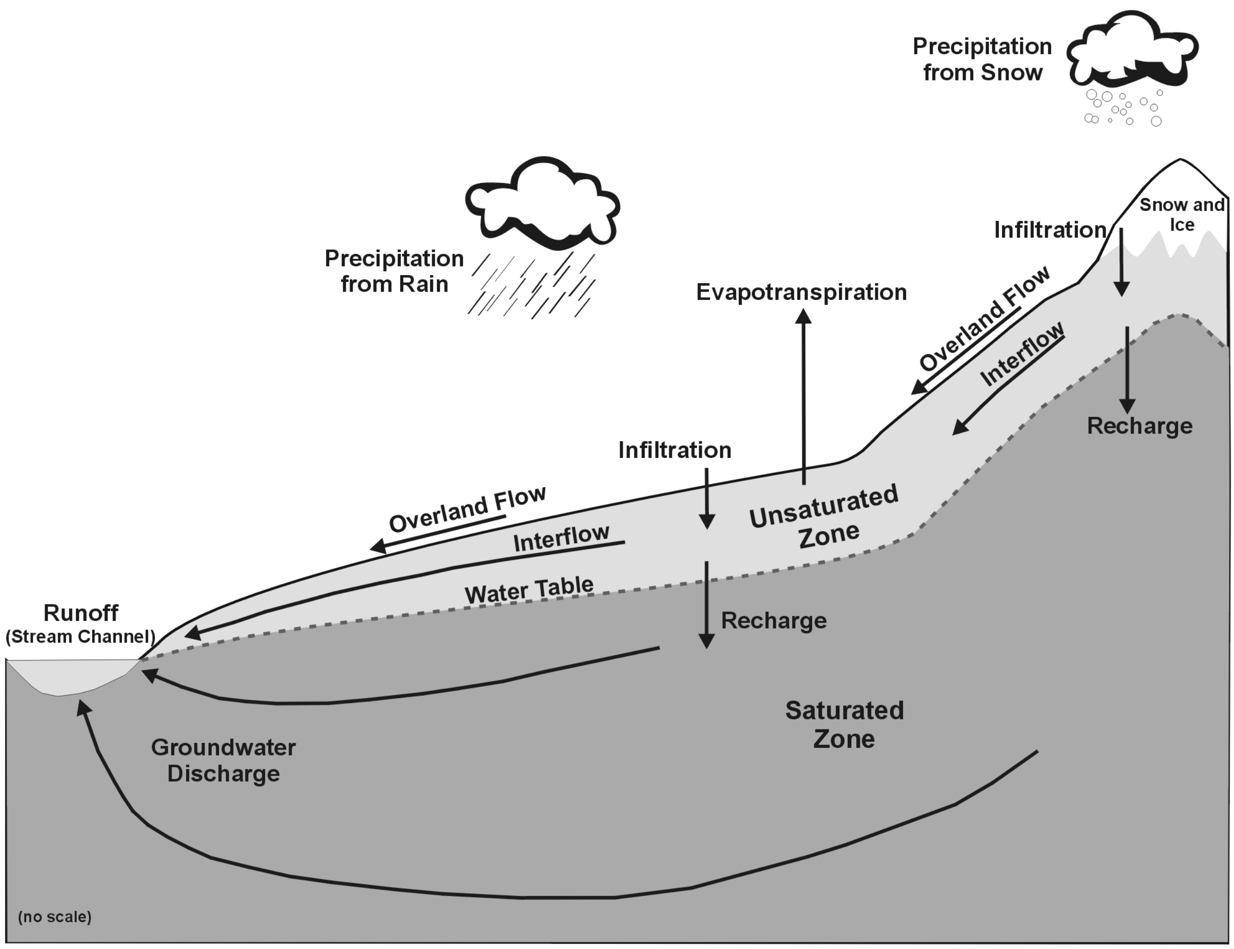

Figure 3. 2- The water cycle in the vicinity of the land surface. Conceptual model based on Fitts, C. R., (2002).

The hydrological services described in the previous section (water supply and water damage mitigation) are closely related to the part of the water cycle that takes place on, or close to, the land surface (Figure 3.2). This phase of the global water cycle may be concisely described as follows (Fitts, 2002; Van Brahana, 2003): (i) water from precipitation reaches the ground surface and infiltrates or generates overland flow (depending on topographic conditions, vegetation cover, soil texture and structure, presence of natural or anthropic impermeable layers, among other factors); (ii) once in the unsaturated zone, water may circulate sub-horizontally (interflow) and emerge, after a short path, in a slope or a river bank; (iii) alternatively, water may circulate downwards in the direction of the water table and recharge the aquifer; (iv) here, groundwater circulates through a saturated medium and finally discharges to a stream (baseflow).

The water supply service depends, first of all, on the volume of precipitation and evapotranspiration. Afterwards, the balance between infiltration and overland flow determines the timing of the subsequent flows. If most of the water from precipitation infiltrates due to a gentle slope allied to a highly permeable soil and adequate vegetable cover, the aquifer recharge rate will probably increase, leading to a greater stream base flow throughout the year. In this case, the water supply service will benefit from unsaturated zone features that favour infiltration, originating greater groundwater resources (which may be exploited through wells) as well as surface water resources that are better distributed in time (which may be exploited e.g. through dams) (e.g. (Lal, 2000; Fetter, 2001)). Water quality greatly depends, among other factors, on the natural attenuation taking place in the unsaturated zone (Fetter, 1999). In fact, the concentration of pollutants decreases as water percolates through the unsaturated zone due to the action of physicochemical and biological processes.

The hydrological services related to water damage mitigation are also closely controlled by the unsaturated zone properties. Once more, the key problem concerns the control of infiltration and aquifer recharge rates by hydropedological features, as well as by the structure of the unsaturated zone (Espinha Marques et al., 2011). The occurrence of floods and soil erosion are greatly determined by the combined effect of vegetation, soil type and topography. For instance, sparse vegetation allied to fine textured soil (clay or silt) is likely to promote overland flow and reduce infiltration, thus increasing the risk of such natural hazards. Furthermore, a highly heterogeneous unsaturated zone (regarding hydraulic conductivity) allied to steep topography may trigger landslides as a consequence of heavy rainstorms (Fernandes et al., 2004).

3.3. Remote sensing of ecosystem functioning for hydrological services provision

Extensive reviews and special issues have been published, over the last decades, about remote sensing and the science of hydrology (Kite & Pietroniro, 1996; Rango & Ahlam, 1998; Pietroniro & Prowse, 2002; Schmugge et al., 2002; van Dijk & Renzullo, 2011; Fernández-Prieto et al., 2012; Su et al., 2012). More recently, some attempts to combine remote sensing and ecosystem services (all categories) have been published (Feng et al., 2010; Ayanu et al., 2012). Here, we will approach remote sensing for the study of hydrological services, particularly satellite techniques and sensors applied to the observation and monitoring of water (liquid, solid and gas phases) in the different Earth reservoirs: atmosphere, cryosphere, surface water, soil/ ground and vegetation. Table 11.1 describes some satellite products of interest for the assessment of each water element, related to water supply and/or water damage mitigation services. We need to advert that this review, although comprehensive, does not describe all the satellite products available.

3.3.1. Water supply

3.3.1.1 Atmosphere

In the Atmosphere, water vapour, clouds and precipitation (rainfall and snow) are important water elements that influence the provision of the water supply service. Water vapour and clouds absorb and emit Infrared Radiation (IR), and clouds also reflect Visible Radiation (VIS), contributing to the energy balance of the Earth (Su et al., 2012). Microwave radiometers are used to measure the emitted radiation, while optical instruments are used to measure the VIS, IR and Near-Infrared Radiances (NIR). The rationale behind cloud observation, and indirectly precipitation (VIS and IR), is the higher cloud reflectance and lower temperature when compared to the Earth surface (Tapiador et al., 2012).

MODIS (Moderate Resolution Imaging Spectroradiometer), on board of Terra and Aqua satellites, which provides since 2000 the Atmosphere product, and SEVIRI (Spinning Enhanced Visible and Infrared Imager), on board of Meteosat-8, are both used to retrieve cloud properties using improved algorithms at high spatial resolution (Kidd et al., 2009; Su et al., 2012). The most advanced measurements using RADAR and LiDAR to retrieve cloud physical properties are Cloudsat and Calypso satellites, launched in 2006 by NASA-CSA (Su et al., 2012). For the water vapour observations (total water column, water vapour profiles, upper tropospheric humidity) some retrieval algorithms and sensors were thoroughly described by Schulz et al. (2009) and Su et al. (2012). As an example, CM SAF (Satellite Application Facility on Climate Monitoring) uses several instruments on-board of

Meteosat and NOAA's operational satellites, to provide cloud and water vapour parameters (Schulz et al., 2009).

Precipitation rates can be better measured by microwave techniques, due to the strong interaction of rain particles and relative insensitivity to cloud cover (Michaelides et al., 2009; Tang et al., 2009). Precipitation satellite products were exhaustively described by Kidd et al. (2009), Michaelides et al. (2009) and Tapiador et al. (2012). Multi-sensor techniques, such as TRMM (Tropical Rainfall Measuring Mission), which holds the TMI (TRMM microwave imager) on passive microwave retrievals and the first space-borne PR (precipitation radar) on active microwave, provide precipitation estimates at 3-hour intervals, from 1997 until present, and it is highly used on global climate models (Tapiador et al., 2012). PERSIANN-CCS (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) is a precipitation algorithm that merges low altitude polar orbiting satellites and geostationary IR imagery. In addition, records are compared to rain gauged observations and adjusted with passive microwave rainfall values to obtain highly accurate rainfall estimates (Sorooshian et al., 2000; Sahoo et al., 2011). Planned to be launched in 2014, the international Global Precipitation Measurement (GPM), will be the follow-on of TRMM and will utilize GPM satellite constellation, carrying advanced instruments that will set a new standard for precipitation measurements from space (Su et al., 2012; Tapiador et al., 2012).

3.3.1.2 Cryosphere

The observation of snow and ice is important, because the timing of cold-water storage in a basin determines different runoff and river flows, influencing water supply timing and water damage mitigation (see level rise and flooding). Different physical properties comparing with rainfall require different sensing techniques (Schmugge et al., 2002). Given the contrasting reflectances between snow and other types of land cover, VIS and NIR bands have been used to map snow. Even though, some limitations still exist related to the similarity between snow and clouds, as well as to the information about snow depth (Wagner et al., 2009). The most common sources on optical medium-resolution for snow and ice mapping are: MODIS snow product with high temporal and spatial resolution; and AVHRR (Advanced Very High Resolution Radiometer) on board of NOAA's family of POES (Polar orbiting platforms).

Microwave radiation (MR) emitted from the underlying ground is scattered in many different directions by snow grains within the snow layer. In turn, MR can be affected by some properties of the snowpack, such as the size of grains, subject of passive and active microwave observations (Schmugge et al., 2002). Snow water equivalent (SWE) is a parameter sensitive to passive microwave signals, based on radiative transfer process. Likewise, Globsnow product combines ground data with passive observations to monitor snow extent and SWE, using SSMR (Scanning Multichannel Microwave Radiometer), SSM/I

(Special Sensor Microwave Imager) and AMSR-e (Advanced Microwave Scanning Radiometer) (Luojus et al., 2010). Active microwave instruments offer ice and snow maps with higher spatial resolution, such as the recently lunched CryoSat mission, at spatial resolution of 5km (Drinkwater et al., 2003).

However, passive and active microwave methods have some limitations that affect the retrievals, namely coarser temporal and spatial resolutions compared to optical observations, and strong sensitivity to snowpack microphysical properties (Tang et al., 2009). A combination of multisensor products, such as IMS (Interactive Multisensor Snow and Ice Mapping System), which gathers information from NOAA-AVHRR, Terra/Aqua MODIS and METEOSAT satellites, is an alternative to overcome those limitations and to generate large scale snow data (Helfrich et al., 2007).

3.3.1.3 Surface water

Surface water encompasses inland and ocean water, both storage and discharge. The observation of surface water contributes to evaluate water supply quantity services, as well as the quality of the water in which satellite observations have been of great importance. Water absorbs energy at NIR and MIR (middle infra-red), whereas soil and vegetation reflect at these wavelengths (Pietroniro & Prowse, 2002). Likewise, optical imagery has been used to map flood plains, lakes and reservoirs, but with constraints related to cloud presence that masks the underlying water, with limitations to water quantification (Alsdorf & Lettenmaier, 2003). To overcome this, radar altimetry has been extensively used to monitor water surface level and, together with elevation, calculate the volume of water (Alsdorf & Lettenmaier, 2003; Su et al., 2012). In the early 1990’s, radar altimeters, such as ERS-1 and TOPEX-Poseidon, started to provide information about very large lakes and reservoirs, continued by the second generation currently operational, ERS-2, ENVISAT, GFO, Jason-2 (Tang et al., 2009). In the coming future, the SWOT (Surface Water and Ocean Topography) mission will overcome the spatial and temporal resolution limitations of current altimetry instruments and include messed water bodies between tracks (Tang et al., 2009; Su et al., 2012). In fact, satellite observations alone cannot measure stream discharge and velocity (Tang et al., 2009). An approach to estimate river discharge is to use remotely sensed hydraulic information, beyond radar altimetry, combined or not with hydrological modelling (this will be developed in hydrological modelling section below) (Bjerklie et al., 2003; 2005). Finally, the space gravimetry mission GRACE provides measurements of water volume, which combined with precipitation and evapotranspiration data is a useful tool to estimate continental freshwater discharge at near real-time (Syed et al., 2010) .

Water cycle	Service	Type	Product/sensor	Satellite	Spatial resolution	Temporal resolution	Costs	Period	Institution/source
Water vapour	Water supply	Optical	Total column water vapour from GOME/SCIAMACHY (Global Ozone Monitoring Experiment)	ERS	80-40km 60-30km	3 days	yes	1995-present	EUMETSAT http://gome.aeronomie.be
			Total column water vapour from MERIS (medium-resolution imaging spectrometer)	ENVISAT	300m	3 days	yes	2005-present	ESA http://www.enviport.org/meris/
			MVIRI (Meteosat Visible and Infrared Radiation Imager)	METEOSAT	5 km	30 min	yes	1977-present	EUMETSAT http://www.eumetsat.int/
			Water vapour profiles and cloud product from AIRS (Atmospheric Infrared Sounder)	Aqua	3-14km	Daily	free	2002-present	NASA http://airs.jpl.nasa.gov
		Passive microwave	Total Precipitable Water product from SSM/I (Special Sensor Microwave Imager)	NOAA's family of POES (Polar orbiting environmental satellites)	15-20km	4 hours	yes	1987-present	NESDIS http://www.ncdc.noaa.gov/
Clouds	Water supply quantity and timing Water damage mitigation (storm and flood prevention)	Optical	Atmosphere product (cloud temperature, height, emissivity...) from MODIS (Moderate Resolution Imaging Spectroradiometer)	Terra	1km	Once or twice a day	free	2000-present	NASA http://modis-atmos.gsfc.nasa.gov/
			Water vapour profiles, cloud top temperature and pressure products from IASI (Infrared Atmospheric Sounding Interferometer)	MetOp-a	1-25km	3 days	yes	2007-present	EUMETSAT http://www.eumetsat.int/
			Cloud product from AVHRR (Advanced Very High Resolution Radiometer)	NOAA's family of POES	25km	Weekly	free	1982-present	NESDIS http://noaasis.noaa.gov/
		Microwave radar	Cloud physical properties	Cloudsat	2.5km	Orbital	yes	2006-present	NASA-CSA http://cloudsat.atmos.colostate.edu
				Calipso (Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observations)	0.3 - 5km	Orbital	yes	2006-present	NASA-CSA http://www-calipso.larc.nasa.gov
Precipitation	Water supply quantity and timing Water damage mitigation (storm and flood prevention)	Optical	Rainfall Hydro Estimator - GOES geostationary satellites	NOAA's family of POES (Polar orbiting environmental satellites)	4km	3 hours	free	2002-present	NESDIS http://www.star.nesdis.noaa.gov/
			MODIS atmosphere product - 36-channel VIS/IR sensor	Terra and Aqua	1km	Daily	free	2000-2002-present	NASA http://modis-atmos.gsfc.nasa.gov/
			SEVIRI (Spinning Enhanced Visible and Infrared Imager)	METEOSAT-8	1km	15 min.	yes	2002-present	EUMETSAT http://www.eumetsat.int/
		Passive microwave	AMSR-e (Advanced Microwave Scanning Radiometer)	Aqua	25km	Sub-daily	free	2002-2011	NASA http://wwwghcc.msfc.nasa.gov/AMSR/
			TMI (TRMM microwave imager)	TRMM (Tropical Rainfall Measuring Mission) for Tropical regions	250m – 5km	3 hourly, daily, weekly, monthly	free	1997-present	NASA+JAXA http://trmm.gsfc.nasa.gov/
		Active microwave	PR (Precipitation radar) in space	TRMM	250m – 5km	3 hourly, daily, weekly, monthly	free	1997-present	NASA+JAXA http://pmm.nasa.gov/node/162
		Multisatellite /sensor and algorithms	PERSIANN (Artificial Neural Networks-Cloud Classification System) database	TRMM and gauged stations	4km	3 hourly, daily, weekly, monthly	free	2000-present	CHRS http://chrs.web.uci.edu/persiann/
			CMORPH (CPC Morphing Technique (Climate Prediction Center))	GEO satellite IR data + passive microwave AMSR-e and TMI	8km	30 min - daily	free	2002-present	NWS http://www.cpc.ncep.noaa.gov/

Table 3. 1 – Examples of Sensors and Satellites to Measure the Elements of the Water Cycle

Snow and ice	Water supply quantity (glaciers) Water damage mitigation (see level rise, flooding)	Optical	Snow product from AVHRR (Advanced Very High Resolution Radiometer)	NOAA's family of POES	25km	Weekly	free	1966-present	NESDIS http://www.nsof.class.noaa.gov/
			MODIS snow product - NDSI (Normalized difference snow index)	Terra and Aqua	500m-1km	Daily, weekly and monthly composites	free	2000-present	NSIDC+DAAC http://modis-snow-ice.gsfc.nasa.gov
		Passive microwave	SWE (Snow Water Equivalent) from AMSR-e (Advanced Microwave Scanning Radiometer)	Aqua	25km	Daily	free	2002-2011	VUA + NASA+NSIDC http://nsidc.org/
			Ice map of Artic from CryoSat mission	CryoSat-2	5-10km (250m)	30 days	yes	2010-present	ESA http://www.esa.int/
		Active microwave	RADARSAT ice monitoring	RADARSAT-1 / 3	500km	Daily	yes	1995-2007-present	CSA+MDA http://www.asc-csa.gc.ca/eng/satellites/radarsat/
		Multisatellite /sensor and algorithms	GLIMS database (The Global Land Ice Measurements from Space) for glaciers	ASTER (Advanced Spaceborne Thermal Emission and reflection Radiometer) combined in a database with satellite imagery and other GIS data for glaciers monitoring	150m	16 days	yes	2005-present	NSIDC+USGS http://www.glims.org
			GlobSnow	Combined ground data with SMMR, SSM/I and AMSR-e	25km	Daily, weekly, monthly	yes	1979-present	ESA http://www.globsnow.info
			IMS (Interactive Multisensor Snow and Ice Mapping System)	NOAA/POES -AVHRR; MODIS; METEOSAT	4-24km	Daily, weekly	free	1997-present	NIC-NOAA/NESDIS http://www.natice.noaa.gov/ims/ims.html
ET	Water supply and drought monitoring	Multisatellite /sensor and algorithms	MOD 16 ET product from MODIS land cover, LAI/FPAR and global surface meteorology (GMAO)	Terra	250m - 1km	16days	free	2001-present	NASA http://modis.gsfc.nasa.gov/
			SEBAL (Surface Energy Balance Algorithm for Land) uses different kinds of information. e.g. surface temperature, hemispherical reflectance and NDVI	e.g. METEOSAT and NOAA-AVHRR	According to the study	According to the study	free	1998-present	Bastiaanssen et al 1998
Surface water	Water supply (quantity, timing and quality) and water damage Water damage mitigation	Radar altimeter	Ocean topography from Jason-2	Ocean Surface Topography Mission (OSTM)	2 km	10days	yes	2008-present	NASA, CNES, EUMETSAT, NOAA http://www.nasa.gov/
		Optical	Surface water extent using visible band sensors e.g. SPOT	SPOT	5 – 25m	26 days	yes	1986-present	CNES http://www.cnes.fr/
			Water quality bands from MERIS (Medium Resolution Imaging Spectrometer)	ENVISAT	300 m	2-3 days	yes	2005-present	ESA https://earth.esa.int/

Table 3. 1 –Examples of Sensors and Satellites to Measure the Elements of the Water Cycle
(Continued)

Water cycle	Service	Type	Product/sensor	Satellite	Spatial resolution	Temporal resolution	Costs	Period	Institution/source
Soil moisture	Water supply quantity and timing Water damage mitigation (landslides and flooding)	Optical	ASCAT (Advanced Scatterometer)	MetOp-a	25km	Daily	yes	2006-present	EUMETSAT+ESA http://manati.star.nesdis.noaa.gov
		Active microwave	ASAR (Advanced Synthetic Aperture radar)	ENVISAT	1-5km	Weekly	yes	2005-present	ESA https://earth.esa.int/
			AMSR-e (Advanced Microwave Scanning Radiometer)	Aqua	25km	Sub-daily	free	2002-2011	VUA + NASA+NSIDC http://nsidc.org/data/amsre/
		Multisatellite /sensor and algorithms	LPRM (Land Parameter Retrieval Model)	AMSR-e,Nimbus SMMR, TRMM TMI, SSM/I	50km	Sub-daily	free	1978-present	VUA http://www.falw.vu/~jeur/lprm/pubs.htm
		Passive microwave	Soil moisture from MIRAS (Microwave Imaging Radiometer with Aperture Synthesis)	SMOS (Soil Moisture and Ocean Salinity)	50km	3 days	free	2009-present	ESA http://www.esa.int/
Groundwater	Water supply quantity	Optical	Visible band (vegetation identification points) and NDVI	Landsat/IKONOS and MODIS	250m	10-30days composites	free (Ikonos yes)	1972-present 1999-present	NASA
			NIR band (temperature of groundwater discharge)	Landsat-5/7	15-60m	16 days	free	1999-present	NASA http://landsat.usgs.gov
		Gravimetry	GRACE Earth microgravity model	GRACE (Gravity Recovery and Climate Experiment)	400-500km	30 days	yes	2002-present	NASA+DLR http://www.csr.utexas.edu/grace/
			GOCE Earth's gravity field and geoid models	GOCE (Gravity field and steady-state Ocean Circulation Explorer)	100km	10-30 days	yes	2009-present	ESA http://www.esa.int/

Table 3. 2 – Examples of Sensors and Satellites to Measure the Elements of the Water Cycle

(Continued)

Development of remote sensing techniques for monitoring water quality began in the early 1970’s. Most of these studies evaluated empirical relationships between spectral properties and the water quality parameters (Ritchie et al., 2003). The factors that affect water quality can be grouped in: (i) those that change the energy spectra of reflected solar and/or emitting thermal radiation from surface waters, which can be measured using remote sensing techniques, such as suspended sediments/turbidity (e.g. (Potes et al., 2011)), algae (i.e. chlorophylls, carotenoids; e.g. (Carvalho et al., 2010; Song et al., 2012), dissolved organic matter (DOM; e.g. (Del Castillo & Miller, 2008; Jørgensen et al., 2011)), oils (e.g. (Jha et al., 2008), aquatic vascular plants (e.g. (Santos et al., 2009; Ward et al., 2012)), and thermal releases (e.g. (Alcantara et al., 2010); and (ii) those that are inferred indirectly from measurements of other water quality parameters (sensible to energy spectra), like most chemicals (i.e. nutrients, pesticides, metals; e.g. (Hadibarata et al., 2012)) and pathogens (Tran et al., 2010a). Multispectral image sensors, such as MERIS instrument on board of Envisat satellite, provide spectral bands with potential applications on suspended sediments, chlorophyll and other water quality parameters (Ayanu et al., 2012). The advantage of using satellite observations tools to identify and monitor surface water quality problems, is the spatial and temporal coverage of the parameters, comparing with the non readily available in situ measurements (Ritchie et al., 2003).

3.3.1.4 Soil and ground

Water under the land surface is observed as soil moisture, which is located in the unsaturated rooting zone, and as groundwater, in the saturated zone (Figure 3.2). Optical sensors operating in VIS and IR bands can indirectly infer soil moisture, through partitioning of the water balance equation elements (Su et al., 2012). On the other hand, due to the dielectric constant propriety of dry soil, which changes in the presence of water, soil moisture is more accurately measured under the microwave bands, both by active and passive retrievals (Schmugge et al., 2002). Active microwave sensors (SAR at local to regional scale and scatterometers for global monitoring) emit an electromagnetic pulse, and capture the returning electromagnetic energy scattered back from Earth that is measured (Su et al., 2012). One example is the Global Soil Moisture product derived from ASCAT (Advanced Scatterometer), on board of the METOP-A satellite from EUMETSAT, which is available from 2006 until present, at a 25 km spatial resolution (Bartalis et al., 2007). In turn, passive microwave sensors measure the radiation emitted from the Earth surface and there are several algorithms to retrieve soil moisture information. One example is LPRM (Land Parameter Retrieval Model), a global soil moisture model that combines historical datasets from1978 to present (Owe et al., 2008). However, passive sensors working at C-band and longer wavelengths are limited in areas with abundant vegetation cover (Tang et al., 2009). To overcome this limitation, the SMOS (Soil Moisture and Ocean Salinity) satellite mission, launched in 2009, is taking observations every three days at a 50 km spatial resolution (Albergel et al., 2011). The advantages of near-real-time observations of soil moisture are: (i) the better understanding of the water cycle, (ii) of how it impacts climate change, (iii) and the improved forecast of natural hazards, such as floods and droughts (Su et al., 2012).

Groundwater was the last component of water cycle taking benefit of satellite technologies, but its monitoring is very important due to significant seasonal and interannual variability. Satellite measurements of vegetation distribution, topography, temperature, soil moisture and gravity have been used to collect information about groundwater presence (Becker, 2006). The gravity measurement, is based on the principle of the redistribution of water in different compartments of the Earth, which changes with the gravitational field (Su et al., 2012). Likewise, groundwater is measured by GRACE (Gravity Recovery and Climate Experiment), launched in 2002, a two-satellite mission to map the static and time varying components of the Earth's gravity field (Ramillien et al., 2008). GRACE provides measurements of groundwater storage change with high accuracy, by separating the contributions of the other water compartments (soil moisture, ocean, evapotranspiration) (Rodell et al., 2006; Llovel et al., 2010). Finally, GOCE (Gravity field and steady-state Ocean Circulation Explorer), launched in 2009, is mapping the Earth's gravity with unrivalled precision and is a complement to GRACE measurements.

3.3.1.5 Vegetation

Estimation of vegetation water content (VWC), from local to global scales, is central to the understanding of water flows in the environment, and it is an important variable for drought and fire monitoring. Remote sensing technologies offer an instantaneous and non-destructive method for VWC assessment (reflectance in NIR and short-wave IR), considering that in situ measurements can be related to spectral reflectance of VWC in a reliable way (Wu et al., 2009). However, this type of methods needs further refinement to account for the observed effects of leaf structure, leaf dry matter, canopy structure and leaf area index (LAI) (Zarco-Tejada et al., 2003).

Canopy water content has been estimated through various vegetation water indices (Yilmaz et al., 2008) composed of bands in these absorption peaks – e.g. normalized difference water index (NDWI), normalized difference infrared index (NDII), maximum difference water index (MDWI), water band index (WBI) – have been proved to be applicable in the estimation of VWC (Chen et al., 2005). Recently, researchers have explored methodologies for VWC estimation through remote sensing techniques based on radiative transfer models, such as PROSPECT and SAILH (Jacquemoud et al., 2009; Suárez et al., 2009).

3.3.2. Water damage mitigation

All the satellites and sensors described before can also be used to monitor water related hazards. Particularly, precipitation is the triggering factor for related water hazards. Therefore, it is important to estimate precise precipitation rates at global scale for accurate risk assessment (Tapiador et al., 2012). The observation of meteorological phenomena from satellite platforms provides a more accurate view when compared to surface observations, with advantages for climate assessment and forecasting of extreme events (Kidd et al., 2009). Floods and related damages can be detected for different periods using optical imagery, for instance from the Landsat series. The past of land surface dynamics can be reconstructed using microwave sensors (SRTM, MODIS, AMSR-e), contributing to predict hazards due to previous events of flooding, coastal inundation and land sliding, especially the more devastating ones (Tralli et al., 2005; Syvitski et al., 2012). The monitoring of ice sheets and melting process is important to follow see level rise and possible coastal inundations and erosion processes. Missions like Cryosat (2010-present) and ICESat (2003-2010) provide a multi-year elevation data needed to determine ice sheet mass balance.

Landslides can be identified using optical images (e.g. Quickbird), and can be forecasted using RADAR and InSar techniques collecting information on geomorphology and soil moisture (Tralli et al., 2005; van Westen et al., 2008). High temporal and spatial resolution satellite can be used to forewarning signal of increased susceptibility to land sliding and help to understand the processes leading to slope failures (Wasowski et al., 2010).

Droughts are caused by water deficit due to increased evapotranspiration and temperature, lack of precipitation and reduced soil moisture. Several indices have used different elements of the water cycle to infer about the severity of drought (vegetation, soil moisture and evapotranspiration) (Su et al., 2012). This is of particular relevance in arid and semi-arid ecosystems, where droughts are a major factor controlling the inter and intra-annual variation in the productivity of the ecosystem and, consequently, the benefits provided by the ecosystem (Hein et al., 2011). Efforts have been made to collect different satellite data to support risk assessment. An example is the Dartmouth Flood Observatory that provides a global water database and critical indices on floods and droughts and can be used for global and regional risk assessments (e.g. global flood risk (Jongman et al., 2012).

3.4. Remote sensing of drivers and pressures of hydrological services

Remote sensing is important to monitor the drivers and pressures that may affect the provision of hydrological services, from the security of freshwater resources to the mitigation of water hazards in the context of climate change. Climate change is a global driver of ecosystem functioning and services, associated to the change in precipitation pattern among other pressures (Figure 3.1). Climate monitoring is therefore crucial for water resource management, and long-term datasets of precipitation have been taken since the late 1970’s with high accuracy from Meteosat and NOAA series satellites (Kidd et al., 2009). Land use change, from urban expansion to farmland abandonment or forest management intensification, is another important pressure on hydrological services. Land use dynamics can nowadays be monitored with very high spatial and temporal accuracy by satellite images, such as Quickbird and IKONOS (Rogan & Chen, 2004).

3.5 Integrating remote sensing data with hydrological modelling

The use of hydrological models enables managers to understand the response of a river catchment to atmospheric forcing conditions, which is important for more accurate water resource management and water hazards forecast and mitigation (Xie & Zhang, 2010).

The increasing demand of spatial data for more complex, physically based and distributed hydrological models, together with the emergence of more sophisticated remote sensing products have increased hydrologists’ interest in the use of remote sensing applications (Kite & Pietroniro, 1996; Pietroniro & Prowse, 2002). In particular, new opportunities have emerged from remotely sensed data to improve hydrological modelling calibration and validation (Montanari et al., 2009). The list of remote sensing products potentially useful for hydrological modelling includes the provision of data on precipitation, land use, soil moisture, discharge and evapotranspiration (Pietroniro & Prowse, 2002).

The advantages of using remotely sensed products extend to the availability of near-real time data, with a complete area coverage, which make possible to perform hydrological modelling even in regions with spatially and temporally scarce ground observations (Grimes, 2008). Focusing on near-real time characteristic, hydrological models can be enriched with time continuity and dynamic information using a family of techniques known as data assimilation (Walker & Houser, 2005). Those techniques merge models and observations accounting for uncertainties from different forcing conditions and parameterizations, improving model performance (Xie & Zhang, 2010). Although remote sensing provides continuous and up-to-date measurements at varying spatial scales, it still relies on ground observations for algorithm development, calibration and validation (Tang et al., 2009).

Remote sensing data can be used to estimate hydrologically important bio-physiographic variables (terrain, land cover/use, soil data) as well as hydrologic-state variables (e.g. precipitation) that influence the water processes in a basin or region (Pietroniro & Prowse, 2002).

3.5.1 Hydrologic bio-physiographic variables

Hydrologic bio-physiographic variables are the spatial input data for physical and distributed hydrological models. Terrain data are used in the delineation and discretization steps of hydrological modelling (Arnold & Fohrer, 2005) .This type of data is collected with high accuracy resolution, mostly from RADAR, but also short wavelength sensors. The most popular and freely available sources are SRTM (Shuttle Radar Topography Mission) by NASA and GDEM (Global Digital Elevation Model) from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). In addition, land cover/use and soil data are especially important for distributed hydrological models, where the hydrological response units are influenced by the spatial variability of land cover and soil characteristics (Pietroniro & Prowse, 2002). There are freely available land cover datasets based on satellite imagery interpretation. For the entire world, Global Land Cover 2000 (1: 5 000 000) is available at the U.S. Geological Survey website. For European countries, CORINE land cover (1:100 000) used satellite imagery interpretation (Landsat, SPOT-4, SOPT-5, IRS-P6 LISS III) to produce a land cover product, which is available for years 1990, 2000 and 2006 with a common classification for all European countries (EEA, 1996). Finally, for soil information, a low-resolution map Digital Soil Map of the World, from the Food and Agriculture Organization of the United Nations (FAO), is also freely available.

3.5.2 Hydrologic-state variables

Hydrologic-state variables derived from satellite observations have been introduced to complement or even replace in situ model input for hydrological modelling (Tang et al., 2009). Some examples are climatological data, evapotranspiration, soil moisture, water storage and discharge derived mainly from satellite sensors, used to calibrate and validate hydrological models (van Dijk & Renzullo, 2011). Evapotranspiration (ET) is the major link between global energy budgets and the hydrological cycle (Smith & Choudhury, 1990). Satellite remote sensing provides routine observations, such as vegetation, energy and land surface temperature, used to estimate ET (Courault et al., 2005). Two kinds of approaches have been taken: (i) energy balance-based physical models, and (ii) empirical models that relate ET to vegetation index measurements across the growing season (Zhang et al., 2009). An example based on the first approach is the widely used model algorithm SEBAL (Surface Energy Balance Algorithm for Land) (Bastiaanssen et al., 1998). SEBAL was introduced in the calibration process of hydrological modelling, with better results when compared to the use of traditional ground based data algorithm for ET calculation (Immerzeel & Droogers, 2008).

Satellite derived hydrologic-state variables are essential in poorly gauged catchments where availability of hydrological ground data is a challenge for the calibration process (Milzow et al., 2011). Some of these variables have been successfully used in several hydrological modelling efforts (Kite & Pietroniro, 1996; Fernández-Prieto et al., 2012). Precipitation is the most important input for hydrological modelling, and several satellite missions with their derived products have estimated it, such as TRMM. In some regions, such as in Amazon basin, the performance of satellite rainfall data from TRMM is comparable to data obtained by rain gauge observations (Collischonn et al., 2008). However, a recent study in China has shown that the use of TRMM data is good for monthly streamflow simulation, but unsuited for daily simulations, when compared to the use of rain gauge observations. Therefore, further developments in the algorithms of satellite based rainfall of daily estimation are needed (Li et al., 2012). Satellite radar altimetry over land allows data to be retrieved for small and narrow water bodies, which can be converted into discharge using rating curve method, to calibrate and validate hydrological modelling (Leon et al., 2006; Calmant et al., 2008). In combination with ground discharge data, it may improve discharge estimates on finer time and spatial scales (Michailovsky & McEnnis, 2012).

3.5.3 Remote sensing applied in SWAT

A combination between ground based measurements and remotely sensed earth observations in a coupled model output is an interesting approach to address more accurately the water balance equation (Tang et al., 2009). A widely used hydrologic model that combines this approach is SWAT (Soil and Water Assessment Tool), developed in the early 1990s by the USDA Agriculture Research Service, USA (Arnold & Fohrer, 2005). SWAT was developed to predict the impact of land management on water resources, performing routines of simulated discharge on monthly or daily time steps. It is a semi-distributed and physically based model.

Improvements to the original SWAT introducing remote sensing data to calibrate and validate have been emerging (Gassman et al., 2007). Also introducing data assimilation techniques to improve model reliability, for instance using soil moisture (Han et al., 2012). Tobin and Bennett (2012) compared the efficiency of different precipitation products (one from rain gauged observations and the others from satellite data) in six watersheds in the USA, generating streamflow under sub-monthly time steps. Comparable performance between TRMM and ground precipitation data was observed. Narasimhan (2005) applied normalized difference vegetation index (NDVI), derived from NOAA-AVHRR sensor, to verify soil moisture simulated by SWAT, as a complement to traditional streamflow calibration and validation. This study showed that simulated soil moisture could be a good indicator of crop stress in semi-arid conditions. In a study of a southern African river, some changes were introduced in the original SWAT code allowing the combination of radar altimetry, precipitation products, SAR surface soil moisture and GRACE total storage changes. Although the estimates of rainfall differed among precipitation products, surface soil moisture and total water storage allowed to identify likely errors in the periods when precipitation had higher discrepancies (Milzow et al., 2011).

3.6 Conclusions and perspectives

This chapter provides an exhaustive review of the many advantages that earth observation offers for the evaluation, management and monitoring of hydrological services. First, because it strongly improves the spatial quality of distributed information when compared to ground based measurements. Likewise, it allows better access to remote regions with poor ground measurements. Secondly, it can offer information on a near-real time base, which is particularly useful to predict natural disasters and activate emergency plans, already highly developed for precipitation alerts (e.g. TRMM). Finally, the use of remote sensing allows the assessment of the three dimensions of hydrological services, i.e. quantity, timing and quality. Considering the consistent and frequent time coverage information of the water cycle, it is possible to improve the study of interannual variability and seasonal behaviour of the water cycle elements (Schulz et al., 2009). Landsat and other images for more detailed analysis of vegetation and land use patterns are available on a planetary scale since the early 1970s.

However, there are still some limitations regarding the parameterization as well as the costs of the observations. The hydrological information gathered by satellite needs a robust parameterization and validation to improve the accuracy and consistency in hydrological studies, preferably using ground-based measurements (Tang et al., 2009; Hein et al., 2011). Although the cost of earth observations can be high, depending on their spatial and temporal resolution, the use of satellite observations seems to show higher cost effectiveness than conventional methods for hydrological parameters observation (Dreher et al., 2000; Pietroniro & Prowse, 2002).

In the future, the increasing number of more sophisticated satellite missions will create new opportunities for observing, analysing and monitoring the different components of the water cycle (Fernández-Prieto et al., 2012). In addition, the integration of remote sensing applications, particularly satellite-derived products, in hydrological modelling has progressed significantly, improving the spatial and temporal resolution of the outputs. A remaining challenge is the development/improvement of satellite algorithms, adapting them to the routines of hydrological models, and further data assimilation process. Moreover, these satellite products should be calibrated and validated according to the environmental characteristics of each region.

Overall, the assessment of water supply and water damage mitigation services can strongly benefit from remote sensing techniques and data, especially from satellite-based products as described above. Satellite products contribute to improve the understanding of the processes and functions behind the provision of hydrological services, on a spatially explicit and near-real time basis. Furthermore, the drivers and pressures affecting the water cycle and the provision of hydrological services can also be assessed and monitored, thereby contributing to a more robust and efficient management of hydrological resources and services.

Acknowledgments

This study was financially supported by Fundação para a Ciência e a Tecnologia (Portugal) through Ph.D grant SFRH/BD/66260/2009 to Claudia Carvalho-Santos. João Honrado received support from Fundação para a Ciência e a Tecnologia (Portugal) through project grant “ECOSENSING” (PTDC/AGR-AAM/104819/2008). Bruno Marcos received support from Fundação para a Ciência e a Tecnologia (Portugal) through project grant “MoBiA” (PTDC/AAC–AMB/114522/ 2009).

Chapter 4

Simulating the effects of land cover and future climate conditions on the provision of hydrological services in a medium-sized watershed of Portugal

Abstract
Both land cover and future climate conditions influence the provision of hydrological services. Therefore, it is important to understand how these drivers will affect water supply and water hazards mitigation, in order to support planning and management of water resources. The purpose of this study is to evaluate the separated and combined effects of land cover and future climate conditions on the hydrology of the Vez watershed, northern Portugal. SWAT (Soil and Water Assessment Tool) was calibrated against daily discharge, sediments, nitrates and evapotranspiration. Good agreement was obtained between model predictions and field observations related with discharge. Results for land cover revealed that the option for one particular scenario would not compromise the overall provision of hydrological services. However, each scenario may be oriented for a certain provision, for instance natural forests of oak for the gradual release of water. For future climate conditions, a statistical downscaling of four General Circulation Models (GCMs), bias-corrected with ground observations was done for 2021-40 and 2041-60, using the representative concentration pathway (RCP) 4.5 scenario. Results show an increase in temperature (spring: 0.32ºC; summer: 2.02ºC) and a decrease in precipitation (-3.9%), more pronounced in summer (-25%). Although climate change has only a modest effect on the total annual streamflow (-7%), the effect on the water levels during summer was more pronounced, between -15% and -38%. This study shows that climate change can affect the provision in two ways, by reducing dry season flow and by increasing flood risks during wet months. This work also examines the combined effect of land cover change and future climate, with different land cover options having different effects on dry flows, flood risk and soil erosion. Results emphasise the need to consider both climate and land cover impacts in adaptation and management options for water at the watershed scale.

Keywords: Climate change; Hydrological services; Land cover; SWAT; RCP 4.5 scenario; Vez watershed.

Carvalho-Santos C., Nunes J.P., Monteiro A.T., Hein L, Honrado J. (under review) Simulating the effects of land cover and future climate conditions on the provision of hydrological services in a medium-sized watershed of Portugal.

4.1. Introduction

Water plays an essential role in the functioning of ecosystems. In addition, humans rely on ecosystems to provide hydrological services and their resulting benefits (Brauman et al., 2007). These include water supply in terms of quantity, quality and timing (for household, agriculture, industry, hydropower, transportation, recreational and spiritual benefits); and water damage mitigation (reduction in the number and severity of floods, decrease in soil erosion and mitigation of landslides) (Brauman et al., 2007; Carvalho-Santos et al., 2013).

Different land cover regimes and climate conditions may influence the future provision of hydrological services (Brauman et al., 2007). For instance, vegetation cover, particularly forests, may influence hydrological services provision differently according to the environmental characteristics of each region (Calder, 2000). It is generally recognized that an increase in forest cover will decrease the annual water yield in a given watershed (Brown et al., 2005; Farley et al., 2005). On the other hand, it will contribute to a decrease in surface runoff, with a consequent reduction of sediment loading, an increase in infiltration rates, and a buffering of water related hazards, particularly floods and potentially a more steady supply of water during dry periods (Ilstedt et al., 2007; Bredemeier, 2011). Hence, modelling how different land cover options will impact the supply of hydrological services is essential to improve land management options, as well as forest and landscape planning (Kepner et al., 2012). Equally, projections for future climate change foresee an intensification of the hydrological cycle in some regions, altering freshwater resource availability, quality and destructive potential (Kundzewicz, 2008). The last report from the IPCC (Intergovernmental Panel on Climate Change) states, with high confidence, an increase in temperatures throughout Europe and decreasing precipitation in southern Europe, with a likely reduction of water availability from rivers and groundwater resources, as well as increasing extreme phenomena such as droughts, heat waves, heavy rainfalls, floods and fires (Kovats & Valentini, 2014). Reports on climate change for Portugal predict a general decrease in water availability in the country (more pronounced in the south) and an increase of seasonal and spatial asymmetries, namely flood risk and water quality problems (Veiga da Cunha & Oliveira, 2002; Nunes et al., 2008). In Galicia, northwest Spain, which has similar environmental conditions to northwest Portugal, climate change is expected to increase temperatures (2ºC to 3ºC) with marked uneven distribution of annual precipitation, meaning more rain in the autumn but drier springs and summers (Álvarez et al., 2011). Likewise, a modification in the pattern of groundwater resources is expected, which would be mainly concentrated in winter, but decreasing substantially in the summer and autumn, exacerbating the current problems in water supply (Raposo et al., 2013). Therefore, understanding the impacts of the several land cover options and future climate conditions is essential to support planning and management of water resources (Khoi & Suetsugi, 2014).

Given the complexity involving the roles and pathways of water in ecosystems, mapping and modelling hydrological services is still a challenge. Hydrological modelling tools, such as SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998), provide a more detailed picture of the water cycle and water resources, whereas ecosystem service modelling tools, such as InVEST (Integrated Tool to Value Ecosystem Services) (Tallis & Polasky, 2009), are easier to use, but provide a more general picture (Vigerstol & Aukema, 2011). In fact, it has been stated that the most robust approach is to apply daily rainfall-runoff models, but this has been rare in the ecosystem services literature (Crossman et al., 2013). Some attempts have been presented in mapping supply and demand of flooding regulating services using the Kineros hydrological model (Nedkov & Burkhard, 2011), and more recently the application of the SWAT hydrological model for various ecosystem services, taking advantage of modelling multiple functions at the same time in a dynamic way (Logsdon & Chaubey, 2013).

SWAT is a widely used hydrological model developed in the early 1990's by the Agriculture Research Service (USDA), USA (Arnold et al., 1998). SWAT was developed to predict the impact of land management on water resources, performing routines of simulated discharge on monthly or daily time steps (Arnold & Fohrer, 2005). It has been successfully applied around the world, including in the southern watersheds of Portugal (Nunes et al., 2008; Yevenes & Mannaerts, 2011), in a northeast watershed of Portugal (Mateus et al., 2014) and in the neighbouring region of Galicia, Spain (Raposo et al., 2013). However, it has not been applied yet to the northwest mountains of Portugal, which are among the rainiest regions of Europe, though precipitation is highly seasonal.

In this context, the objective of this research was to apply the SWAT hydrological model to a medium-sized watershed in northwest Portugal, and to develop a set of simulations to support land planning options under different land cover and future climate conditions. Specifically, the following three questions were addressed: i) Would land cover change, and particularly the expansion of forest areas be reflected on hydrological services provision? ii) What would be the influence of future climate conditions on hydrological services provision, considering a medium emission scenario? and iii) What would be the combined effects of land cover and climate change on the future provision of hydrological services? Finally the implications of the results to support a preventive and adaptive management of medium-sized watersheds were discussed, with an emphasis on the societal benefits related to water supply and hazard mitigation.

4.2. Methods and Data

4.2.1. Study area

The study area was the watershed of river Vez, a medium-sized watershed (252 Km^2) located in the Soajo and Peneda mountains, northwest Portugal (Figure 4.1). The Vez is one of the main tributaries of river Lima, a major river in northwest Iberian Peninsula. Annual precipitation in the watershed varies from 1 000 mm/year in lowlands up to 3000 mm/year in highlands (wet years), mainly concentrated in the autumn and winter months. The climate presents a Mediterranean type of rainfall regime in lowlands, whereas in highlands rainfall seasonality is not so sharp and the climate is considered Temperate Atlantic with a sub-Mediterranean regime (Mesquita & Sousa, 2009). Average annual observed precipitation and temperature for the study period (1999-2008) were 1 500 mm/year, and 13.8 ºC, respectively. Average annual observed discharge (2003-2008) at Pontilhão de Celeiros hydrometric station was 1 040 mm/year. According to those values, the runoff generation ratio (Q/PP) shows that about 70% of rainfall becomes discharge, which is typical from a mountainous river type of regime. Topography is complex with elevation ranging from 30 m to 1 400 m, and slopes above 25% shaping 58% of the watershed. Granites and some schist characterize the regional geology, while five major soil types characterize the watershed (Figure 4.1c): Humic Regosols (67%) and Leptosols (9%) prevail in highlands; Dystric Antrosols (22%), Fluvisols (1%) and Urban (0.56%) in lowlands. In terms of land cover (Figure 4.1b), open areas of bare rock and heath, scrubland (broom) and transitional forest areas occupy the highlands, whereas agricultural and forest areas (common oak, maritime pine, and eucalyptus) are common in lowlands (Table 4.1). The absence of reservoirs and other water management infrastructures provides this watershed favourable conditions for studies addressing land cover/hydrological services provision relationships. In the last two decades, summer fires and the erosion that follows have been degrading the already shallow soils, as well as keeping vegetation in a constant low/high shrubland state. Shrubland areas occupy about 40% of the watershed (Figure 4.1a). During intensive precipitation episodes, floods in Arcos de Valdevez (a town close to the outlet of the watershed) may occur causing mainly material damages (Appendix C, Table C.1). Therefore, understanding how land cover change as well as future climate conditions may affect the provision of hydrological services in the Vez watershed is of high importance for an effective land management.

Table 4. 1 - Land use classes used in SWAT (Figure 4.1a).

SWAT Class	Identification	Major vegetation species	%
URLD	Urban low density	-	4
CORN	Agriculture - Corn (80%) and Pasture (20%)	Corn and *Lolium multiflorum*	18.7
PINE	Pine	*Pinus Pinaster* Aiton	7.3
OAK	Oaks and other broadleaved trees	*Quercus robur, Quercus Pyrenaica, Castanea sativa, Betula celtiberica, Alnus glutinosa, Salix atrocinera*	8.7
EUCL	Eucalypts	*Eucalyptus globulus*	0.3
BSVG	Baren rock and sparsely vegetated	Heath (*Erica spp.)* and dry perennial grasslands	13.8
MIGS	Atlantic shrubland (80%) with mixture shrubland with sparse trees (20%)	Heath and Gorse *(Erica australis, Calluna vulgaris, Pterospartum tridentatum subsp, Catabricum, ulex* sp.) Broom (Cytisus spp.) and transitional forest (*Quercus robur*)	47.2

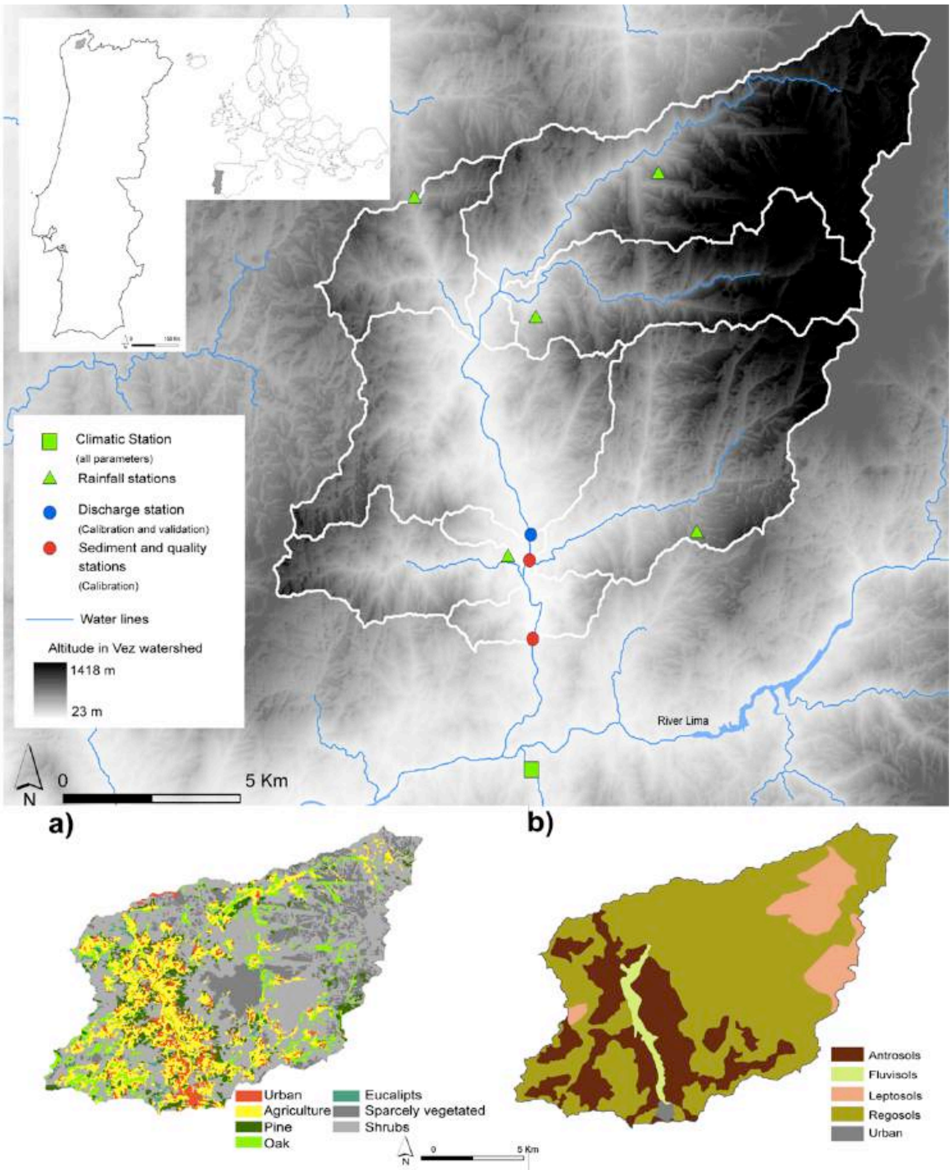

Figure 4. 1 – Location map of Vez watershed in northwest Portugal with 10 sub-basins (white limits), and the Digital Elevation Model of the region (shadow); a) Land cover map, 2006 (SIGN II, 2008); b) Soil map (Agroconsultores and Geometral, 1995).

4.2.2. Input data and SWAT setup

SWAT is a physically based semi-distributed model with daily and monthly calculations of hydrological balance parameters in the watershed (Arnold et al., 1998; Neitsch et al., 2011). The watershed is divided into homogeneous simulations units, the Hydrologic Response Units (HRUs), each consisting of a unique combination of land use, soil type, and slope features (Gassman et al., 2007). SWAT uses the curve number (CN) equation method to predict surface runoff from rainfall for different types of soil and land cover (Arnold et al., 1998). SWAT includes also routines allowing the simulation of vegetation growth from seedling to mature stands, considering plant phenological development, leaf area, radiation interception, and biomass (Gassman et al., 2007). SWAT itself only gives information on the capacity of provision for hydrological services (potential supply of services; Table 4.2). Further analysis should be carried out to have the demand side evaluated for a complete hydrological services study.

Table 4. 2 - Potential hydrological services provision related to the SWAT outputs indicators presented in this study.

Hydrological service	SWAT outputs/indicators
Water supply	
Quantity	Total annual water yield (mm) and monthly discharge (m^3/s)
Timing	Flow duration curves (Q95 - m^3/s); soil water content (mm)
Quality	Nitrate concentration (mgN/l); nitrogen export (kg/ha.yr)
Water damage mitigation	
Erosion control	Soil erosion (t ha.yr); % of the basin under soil erosion risk
Flood regulation	Flow duration curve (Q5 - m^3/s); soil water content (mm)

Input datasets and sources for SWAT calibration in the Vez watershed are presented in Table 4.3. Land cover classes of the original dataset were aggregated into seven major groups, representing the similarities in terms of hydrological traits (Table 4.1). Five major soil groups were used (Figure 4.1b). The generic parameterization of vegetation and soil was based on a previous SWAT study in Portugal (Nunes et al., 2008). Subsequently, parameterization was adapted according to the vegetation characteristics of the study region based on literature with further refinement using the MODIS ET product (see section 2.4 and Table 5). Climatic parameters (Table 4.3) were used from 5 rainfall stations inside the watershed for precipitation, and 1 climatic station outside (5 km) for the other climatic variables (temperature, solar radiation, humidity and wind speed). Simulation period was limited to five years because of data availability and even during this period linear regression analysis were performed to fill data gaps, in particular for days with less than 20 hours of records. For regression analysis, data correlation with 10 rainfall stations surrounding the watershed was considered. Data gap filling is important for precipitation representativeness and model performance (Stisen et al., 2012).

Model setup was done using the ArcSWAT 2009.93.7a interface for ArcGis (Winchell et al., 2010). A digital elevation model (DEM) was used for watershed discretization and delineation, resulting in 10 sub-basins. Subsequently, slope, land cover and soil data (Table 3) were applied for model parameterization, resulting in 185 HRUs (using a 50 ha minimum threshold to reduce the number of insignificant combinations). Slope was divided in 3 classes, defined in order to represent the heterogeneity of this variable in the watershed: 0-10%; 10-25%; > 25%. The major land cover class MIGS was defined as 80% shrubland and 20% of degraded forest and tall shrubs (Table 4.1). Also the class CORN was divided into 80% corn and 20% pasture. In addition, two management operations were applied for corn and pasture based on knowledge and fieldwork on crop management practices in the watershed. For corn, first a tillage operation was applied by the end of April, followed by a model-managed fertilization, based on soil N deficiency, with 15-15-00 fertilizer (175 kg/ha maximum) starting in early May. Finally, harvest operations were applied in September. In October a tillage operation for winter pasture was applied, which is finally harvested in late March to start the corn cultivation. Some fields, mainly in the northern part of the watershed are permanent pastures. 2 grazing operations were implemented (April and September), along with model-managed fertilization with daily fresh manure. In addition, a management operation was created for one land-cover scenario, which must take vineyards into account. This includes a model-managed fertilization with 22-14-00 fertilizer (40 kg/ha maximum) starting in February, and a harvest operation in September.

Table 4. 3 - SWAT data variables for model setup and calibration/validation.

Variables	Source	Description
DEM	(IGeoE, 2012)	20m resolution grid derived from contour line map 1:25 000
Land cover	(SIGN II, 2008)	Land cover map 2006, 1:25 000. Classes were aggregated into 7 main cover classes (see Table 4.1)
	(IGP, 1990)	Validation period - Land cover map 1990, 1:25 000
Soil	(Agroconsultores and Geometral, 1995)	Soil map 1:100 000, with 5 main soil types (Humic Regosols, Humic Leptosols, Dystric Fluvisols, Antrosols and Urban)
Rainfall	SNIRH - National Hydrological Resources Information System (SNIRH, 2012)	Inside the basin, hourly rainfall (mm) data were collected for 5 stations and turned into daily values (see Figure 4.1); Calibration period: 1999-2008 (4 year initialization period) Validation: 1984-1989
Climate (other variables)		Hourly values were converted into daily temperature (min., max. Cº), solar radiation, relative humidity and wind speed (m/s) from climate station Ponte da Barca (see Figure 4.1)
River discharge		Hourly observed river stage were converted into daily river discharge values (m^3/s) and averaged for the basin using stage-discharge relationships (see Figure 4.1) Calibration period: 2003-2008 Validation: 1984-89
Total suspended solids (TSS)		Sparsely daily observations were taken from two sediment stations (period 2003-2008)
Nitrates (NO_3)		Sparsely daily observations were taken from two quality stations (period 2003-2008)

Finally, the model was forced with daily climatic parameters (precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed) for the period 2003-2008. A four–year (1999–2002) warm-up period was used to minimize the impacts of uncertain initial conditions. To improve model performance, 10 elevation bands for precipitation were established with a degree of change of 1 300 mm/Km (northern sub-basins) and 1 100 mm/km (southern sub-basins). These elevation bands were calculated using precipitation records of 20 years (non consecutive) from the stations inside the basin, in relation to the altitude. To improve temperature inputs, we used the lapse suggested in the literature for northwest Portugal, of a 5ºC decrease on average per 1km altitude (Ribeiro, 1945). Evapotranspiration was estimated using the Hargreaves equation, since preliminary runs with Pennan-Monteith equation produced unsatisfactory results, mainly due to the low quality of wind-speed records.

4.2.3. Calibration and validation against discharge

To reduce uncertainty in hydrological model predictions, parameters must be properly calibrated against observed values, especially and foremost against discharge (Engel et al., 2007). The observed daily discharge data at the Pontilhão de Celeiros hydrometric station (Figure 4.1) was used for this exercise. Here, a split-sample approach was applied, using part of the dataset for calibration and an independent dataset for validation, without further adjustment. SWAT calibration was done manually adjusting some sensitive parameters against daily-observed discharge for the period 2003-2008 (Table 4.4). Validation was done for the period 1984-1989 against daily-observed discharge.

Table 4. 4 - Modified SWAT general parameters for the entire Vez watershed.

Parameters	Description in SWAT	Initial value	Calibration
Calibrate streamflow			
Alpha_BF	Baseflow alpha factor (days)	0.048	0.2
RCHGR_DP	Deep aquifer percolation fraction	0.05	0
GW_delay	Groundwater delay time (days)	31	1
CN2	Curve number for moisture condition	various	-10 (added to all classes)
DEPIMP_BSN	Depth to impervious layer (mm)	0	2000
Calibrate sediments			
SLSUBBSN	Average slope length (m)	(automatically estimated)	9
USLE_P	Support practice factor	1	0.05 (Corn/PAST)/ 0.5 (Vine)
USLE_K	Soil erodibility factor	0.26	0.02

* Only applied to CORN and PAST with slope above 10%

Model performance was evaluated with statistical measures commonly used in hydrological modelling, namely the coefficient of determination (r^2), the percentage bias (PBIAS), and the Nash–Sutcliffe-Efficiency (NSE). The corresponding equations and the scale of goodness can be found in Moriasi et al. (2007).

4.2.4. Model verification for Leaf Area Index (LAI) and Evapotranspiration (ET)

Traditionally, calibration and validation in SWAT studies are based only in streamflow parameters, namely discharge and water quality, which can mask whether the internal catchment processes are simulated correctly, particularly the ones related with vegetation growth and evapotranspiration (ET) (Strauch & Volk, 2013). This becomes important when the objective is to simulate the influence of land cover changes on hydrological processes. In the absence of locally measured vegetation parameters (which is the most accurate approach for vegetation growth simulation), model simulations may rely on the adjustment of the SWAT generic vegetation parameters database, according to the vegetation traits of each region. Here, key vegetation parameters were adjusted to optimize LAI and ET based on values expected from the literature (Table 4.5). In addition, simulated values were compared to annual evapotranspiration for different land cover classes taken from MOD16A2 during 2000-2008 (Table 4.6). MOD16A2 is a 1 km^2 resolution product from the Moderate Resolution Imaging Spectroradiometer sensitive to transpiration by vegetation, evaporation from canopy and soil surfaces (MODIS, 2010). Pure land cover pixels (≥ 75% occupied by a single land cover type) from MOD16A2 were selected across northwest Portugal, since the Vez watershed is too small to contain a representative number of 1 km^2 pure land cover pixels (see Appendix B, Figures B.1 and B.2).

4.2.5. Model verification for Total Suspended Solids (TSS) and Nitrates (NO_3)

Given the limited amount of observed TSS and nitrate data, a comparison was made between the SWAT simulated values against estimated in streams, calculated from the existing observations. Observed data consisted of one measurement per month of TSS and nitrates at two water quality stations (Figure 4.1), during the period 2003-2008. The existing data was not sufficient for a complete calibration and validation study, and therefore a simple model calibration and verification was performed. In both cases, the lack of observed values for 1984-1989 prevented a full split-sample approach, and the poor quality of observations avoided a more in-depth analysis than a simple verification.

Existing TSS data were used to calculate a sediment rating curve with a power function, estimating daily sediment yield from daily discharge (Lane et al., 1997). Discharge simulations from the calibrated SWAT model were used for this purpose. The following sediment rating curves were derived: 0.0018**discharge* $^{1.1873}$, with = r^2 0.85, if flow < 40m^3/s; 0.0001**discharge* $^{1.9665}$, with = r^2 0.93, if flow > 40 m^3/s. These curves were used to estimate daily sediment yield values from SWAT simulated discharge, which were then compared with monthly sediment yield modelled by SWAT (Table 4.6).

For nitrates, existing measurements were considered representative of at least the typical value and seasonal variability for this parameter, although not of the variability with discharge. Nonetheless, each measured value was assumed to be representative of the days with no records for the respective month, and used together with simulated discharge to calculate daily nitrate export. These estimates were compared with SWAT simulations for total nitrate exports at the monthly scale.

Table 4. 5 - Modified SWAT parameters by land cover for LAI/ET and erosion calibration in crop and management (.mgt) databases.

Parameter	**Description**	**Calibrated (initial values)**					
		PINE	EUCL	OAK	MIGS	CORN	BSVG
T_BASE	Minimum temperature for plant growth (ºC)	9 (0)	9 (8)	9 (10)	9 (12)	9 (-)	9 (12)
T_OPT	Optimum temperature for leaf development (ºC)	23 (30)	22 (-)	23 (30)	22 (25)	25 (-)	23 (25)
BLAI	Maximum potential leaf area index (m2 /m2)	4 (5)	3.7 (5)	6 (5)	2 (2.25)	5 (6)	1.5 (-)
ALAI_MIN	Minimum leaf area index for plant during dormant period (m^2 /m^2)	3.9 (0.75)	3.4 (4)	0.75 (-)	1.8 (0)	0 (-)	1.4 (0)
MAT_YRS	Number of years required for tree species to reach full development (years)	30 (50)	15 (-)	50 (-)	n/r	n/r	n/r
CHTMX	Maximum canopy height (m)	25 (10)	25 (-)	20 (6)	2 (1)	2 (2.5)	1 (-)
RDMX	Maximum root depth (m)	12 (3.5)	12 (-)	10 (3.5)	1.5 (2)	1 (2)	1 (2)
PHU_PLT (.mgt)	Total number of heat units for plant maturity	3500	3500	3500	1800	1800	1800
USLE_C	Minimum value of USLE C factor for water erosion (factor)	0.001 (-)	0.001 (-)	0.001 (-)	0.001 (0.003)	0.005 (0.2)	0.002 (-)
OV_N (.hru)	Curve number for moisture condition	0.8 (0.14)	0.4 (0.1)	0.8 (0.14)	0.8 (0.15)	0.17 (0.14)	0.4 (0.15)
Bibliography	(Sabaté et al., 2002; Breuer et al., 2003; López Gonzalez, 2006; Nunes et al., 2008; Barbier et al., 2009; Vitale et al., 2011; Clark et al., 2012)						

n/r – not required; (initial value).

A final verification of the exports from sediments and nitrogen by land cover was made, since good model performance for streams does not imply an adequate simulation of differences between land covers. Model results per land cover were compared with typical values for Portugal and other Mediterranean regions presented in the literature for soil erosion (Hooke, 2006; Cerdan et al., 2010) and nitrogen exports (Rial-Rivas, 2007; Machado, 2012). The comparison focused mainly on the relative differences between land covers for both parameters (Table 4.6).

Model performance for calibration of sediments and nutrients in streams was evaluated with the same statistical measures of performance referred before (r^2; PBIAS and NSE). For the land cover scale, the data only allowed for a simple comparison. Some sensitive parameters were adjusted in SWAT for sediments (Table 4.4 and 4.5). In particular, erosion by land cover type was adjusted through the USLE_C parameter (Table 4.5). For nitrates and nitrogen, no parameters were modified other than the maximum amount of mineral N allowed to be applied in the management operations.

Table 4. 6 - Comparison between the average annual evapotranspiration, soil erosion and nitrogen rates by land cover (simulated by SWAT) with the values from the literature and MODIS ET.

	ET (mm)		Soil erosion rates (t/ha.yr)			N export (kg/ha.yr)	
Land cover	**SWAT**	**MODIS**	**SWAT**	**Cerdan et al. (2010)**	**Hooke (2006)**	**SWAT**	**Literature**
Corn + pasture rotation	588	737	0.017	0.84	3.6	9.37	16.8 (3.9 – 40.2) (Rial-Rivas, 2007)
Vineyard			0.17	8.62	13.5	1.51	
Eucalypt	647	740	0.002	0.18	1.1	0.34	0.5
Pine	691	763	0.001			0.25	1.4
Oak	599		0.003			0.46	(Machado, 2012)
Mixed trees/shrubs	495	660	0.002	0.54	0.48	0.42	
Shrub			0.002			0.24	
Pasture	433	-	0.003	0.32	-	0.25	
Sparsely vegetated	461	457	0.005	-	4.77	0.28	

4.2.6. Scenarios

4.2.6.1. Land cover

In the last 50 years, landscape changed significantly in river Vez region. For the period 1958-1995 a large decrease in agricultural areas and low shrublands, counteracting with an increase in tall shrublands and forests was documented, probably related with land abandonment and emigration (Moreira et al., 2001). Since the 1990's, forest declined 15% while low shrublands expanded 14%, mainly related with increasing fire occurrence and intensity, highlighting the major fire that occurred in August 2006 (Proença et al., 2010a). Considering this, our land-cover scenarios were developed according to four possible trends expected to Vez watershed, taking into account the current simulation as a reference scenario (Table 4.7). Three of them imply some management in the territory: (i) Oak - conservation with an increase of autochthones and deciduous tree species, in particular common oak (Quercus robur) in areas now covered with shrubs; (ii) Eucalyptus/pine - intensification of forest area with fast-growing evergreen tree species, such as eucalyptus (Eucalyptus globulus) and maritime pine (Pinus pinaster Aiton) in the shrubland areas; and (iii) Agri/vine - agriculture with the spread of corn and vineyards in the shrublands close to agricultural areas. The last scenario, (iv) Low vegetation - considers that environmental pressures, such as grazing or fires, will lead to degradation with low and sparse vegetation. Classes were manipulated using the same land-cover map (2006). All the scenarios keep the present urban, agricultural and sparsely vegetated areas as static across the landscape (Table 4.7).

Table 4. 7 - Land cover scenarios considered for SWAT simulation period 2003-2008. Urban areas (4%) are constant.

% Land cover	**Current**	**Oak** Conservation	**Eucalyptus/pine** Intensification	**Agri/vine** Corn/vineyard	**Low vegetation** Degradation ()
CORN	18.7	18.7	18.7	18.7	18.7
PINE/EUCL	8	-	**63.5**	-	-
OAK	8.7	**63.5**	-	-	-
BSVG	13.8	13.8	13.8	13.8	**60.6**
MIGS	47.2	-	-	16.7	16.7
VINE	-	-	-	**46.8**	-

4.2.6.2. Future climate

To simulate the effect of future climate conditions, two scenario periods were considered, 2021–2040 and 2041-2060. SWAT was forced with an ensemble of climate model simulations for scenario RCP 4.5 (representative concentration pathways) from the IPCC AR5 assessment report (Meinshausen et al., 2011). RCP 4.5 is a medium stabilization scenario, which assumes that all nations of the world undertake emissions mitigation policies simultaneously and effectively (Thomson et al., 2011; Vuuren et al., 2011). The ensemble approach incorporated the spread of individual ensemble members to reduce uncertainty (Déqué et al., 2007). The ensemble was composed by four GCMs (General Circulation Models) members from the coupled model intercomparison project phase 5 (CMIP5): CNRM-CM5 (Centre National de Recherches Meteorologiques, France), CSIRO-MK3.6 (Commonwealth Scientific and Industrial Research Organisation, Australia), MRI-CGCM3 (Meteorological Research Institute, Japan) and MPI-ESM-LR (Max Planck Institute for Meteorology, Hamburg). In order to compare model fields for the ensemble, models were regridded to the coarsest resolution model (1.875º x 1.875º) using a bilinear interpolation algorithm. For each GCM, the variables precipitation, maximum and minimum temperatures were subject to a linear scaling approach for bias correction (Lenderink et al., 2007; Hurkmans et al., 2010). This approach applied month correction factors to daily-modelled time series of the given month. For temperature, the station Viana do Castelo (about 40 km from the watershed) was used, whereas for precipitation data were collected from two stations inside the watershed. Correction factors are determined as differences (temperature) or quotients (precipitation) between long-term mean of observed and GCM control data. Three 20-years windows were used for all variables: 1981- 2000 (baseline), 2021-2040 and 2041–2060 (scenario periods). The baseline period for temperature variables was affected by a lack of data between September 1996 and June1997, due to a shutdown in measurements. Moreover, our analysis relied on a 20-years period instead of a climate normal (30-year period) also due to the lack of data before this period.

Bias corrected daily scenario temperature and precipitation variables ($Tmax^{scen}$ d,m; $Tmin^{scen}$ d,m; P^{scen} d,m) were estimated by adding or multiplying the long-term monthly correction factors to the modelled daily time series:

Eq. (B.1) $Tmax^{scen}_{d,m} = Tmax^{ensemb\ scen}_{d,m} + (Tmax^{obs}_{m} - Tmax^{ensemb\ con}_{m})$

Eq. (B.2) $Tmin^{scen}_{d,m} = Tmin^{ensemb\ scen}_{d,m} + (Tmin^{obs}_{m} - Tmin^{ensemb\ con}_{m})$

Eq. (B.3) $P^{scen}_{d,m} = P^{ensemb\ scen}_{d,m} \cdot (P^{obs}_{m} / P^{ensemb\ con}_{m})$

where $Tmax^{ensemb\ scen}_{d,m}$, $Tmin^{ensemb\ scen}_{d,m}$ and $P^{ensemb\ scen}_{d,m}$ are the ensemble modelled daily minimum and maximum temperature, and precipitation for the scenario periods. $Tmax^{obs}_{m}$, $Tmin^{obs}_{m}$ and P^{obs}_{m} are monthly long-term mean of observed maximum and minimum temperature, and precipitation. $Tmax^{ensemb\ con}_{m}$, $Tmin^{ensemb\ con}_{m}$ and $P^{ensemb\ con}_{m}$ are the monthly long-term mean of the control period for maximum and minimum temperatures and precipitation. Monthly correction factor approach was adopted to reduce considerable day-to-day variability in the correction factors, which may occur when using daily correction factors.

4.3. Results and discussion

4.3.1. SWAT model performance

The comparison between daily observed and simulated discharge in the calibration and validation periods indicated that SWAT was able to capture and reproduce the average flows and seasonal variations in Vez watershed, except during major high flows or extreme conditions (Figure 4.2). Predictions on monthly discharge were highly accurate (NSE = 0.87 and PBIAS = -13%) (Table 4.8), while daily simulations performance can be considered good (NSE = 0.76 and PBIAS = -15%) (Moriasi et al., 2007). Validation performance statistics (1984-1989) can be considered good for monthly simulation (NSE = 0.73 and PBIAS = 6%), but only satisfactory for daily (NSE = 0.38 and PBIAS = 6%) (Table 4.8). This may be partly related to the difference in the accuracy of climatic datasets for the validation period, particularly for precipitation, in which existing data was reported as daily sums at

9:00hrs, while streamflow was reported at 24:00hrs, causing a mismatch between the input and output data of the model, more relevant at the daily scale. In any case, lower performance on validation in respect to calibration simulations, as well as lower accuracy on daily regarding to monthly predictions, are typical pattern also for other studies (Engel et al., 2007).

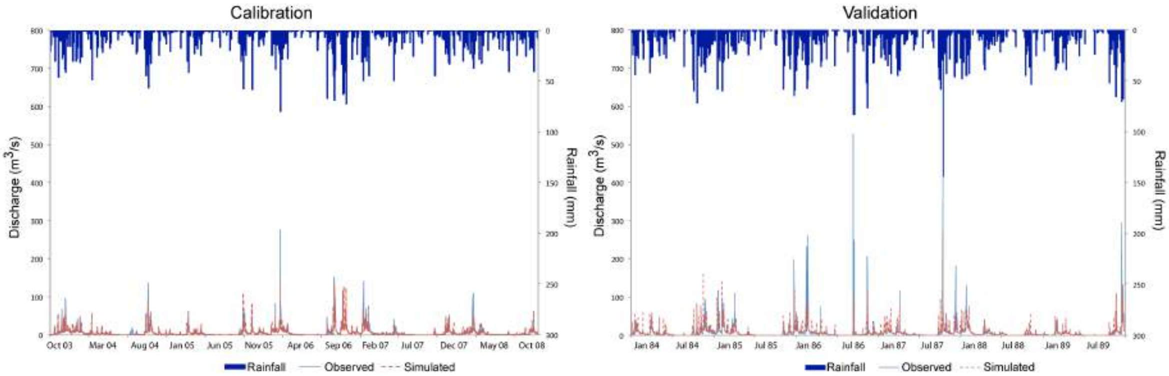

Figure 4. 2 – Daily observed and simulated discharge for calibration and validation period, after parameter calibration (table 4.4 and 4.5). Performance statistics are presented in Tables 4.8 and 4.9.

Table 4. 8 - Calibration and validation goodness-of-fit statistics for discharge in SWAT model.

	Calibration (2003-08)		**Validation (1984-89)**	
	Daily	*Monthly*	*Daily*	*Monthly*
R^2	0.76	0.87	0.40	0.73
PBIAS (%)	-15	- 13	6	6
NSE	0.73	0.86	0.38	0.73

A comparison between MOD16A2 ET values per land cover (Table 4.6) indicates that forest related covers have the highest ET values in the region, followed by agriculture. In turn, sparsely vegetated has the lowest ET values, being the most similar when compared to the simulated by SWAT. There is a difference of 100-150mm between the ET values from MODIS and the simulated by SWAT, with the latter showing the lower values by class. As the LAI achieved by SWAT after parameterization represents the values from each land cover class presented in the literature, the use of MODIS ET was convenient to verify the accurate simulation of the relative differences among land cover classes, rather than approximate the values.

The calibration of sediments was not adequate in terms of model performance statistics, but this could be expected from the low data availability and related estimation uncertainty (Table 4.9). Several studies have presented similar issues in sediments and/or nutrients calibration due to data limitations (De Girolamo & Porto, 2012; Molina-Navarro et al., 2014;

Zabaleta et al., 2014). In this case, a difference of one order of magnitude between observed and simulated sediments was evident (PBIAS = 102.9% and 65.3%), but with a good correlation (monthly R^2 = 0.80 and 0.79). The soil erosion rates simulated by SWAT for each land cover are low, when compared to the ones presented in the literature (e.g. forests: 0.001 - 0.003 t/ha.yr in SWAT simulation; 0.18 – 1.1 t/ha.yr in the literature) (Hooke, 2006; Cerdan et al., 2010). This can be attributed to several factors, including soil stoniness, which leads to low soil erosion, and the presence of agricultural terraces in the Vez watershed (Cerdan et al., 2010). In addition, soil erosion is scale-dependent, considering that values reported in the literature are usually for hillslopes, while SWAT considers sediment yield at larger scales, where rates are expected to be lower (de Vente & Poesen, 2005). Therefore, the low simulated erosion rates were considered consistent with what is expected for the study site, especially given the low observed TSS data.

Regarding nitrates, the simulation can be considered satisfactory (NSE = 0.38; and PBIAS between -13% and 30.2%). The simulated nitrogen exports are similar to values observed for a forested watershed with eucalypts and pines in central Portugal (Machado, 2012) (Table 4.6). When comparing arable land, simulated values are inside the range reported for Galician watersheds (Rial-Rivas, 2007).

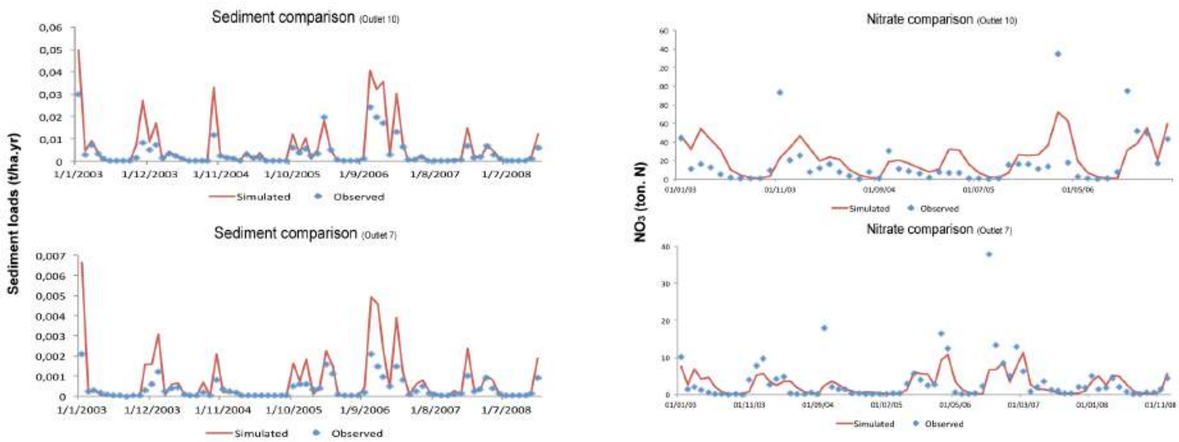

Figure 4. 3 – Comparison between monthly observed and simulated values for sediments (t/ha.yr) and monthly nitrates (ton. NO_3), after parameter calibration.

Table 4. 9 - Calibration goodness-of-fit statistics for sediments and nutrients in SWAT model.

	Sediments		Nitrates	
	Outlet 7	*Outlet 10*	*Outlet 7*	*Outlet 10*
R^2	0.80	0.79	0.39	0.38
PBIAS (%)	102	65.3	-13.3	30.2
NSE	-1.98	0.13	0.38	0.38

Overall, a good agreement was obtained between model predictions and field observations for discharge. Given the limitation of observed data, the calibration of sediments and nitrates is not adequate in terms of statistical performance (Table 4.9). However, when a good performance for hydrological simulation is combined with an appropriate parameterization of soil and land use, SWAT can still be a reliable tool for water quality and soil erosion evaluation (Panagopoulos et al., 2011). Considering the comparison between the limited observed data and the values presented in the literature, model outputs related with sediments and nitrogen were considered valid, while acknowledging the uncertainty associated with the data.

4.3.2. Land cover effects on hydrological services provision

The annual hydrological balance in Vez watershed (Figure 4.4a) showed that the seasonality of the water yield follows the precipitation pattern, and the period in which evapotranspiration is fed by soil moisture is short (June and July). Both situations show the high humidity of the watershed.

Under present climate conditions, results indicated that the effects of land cover on the water processes are moderate in the Vez watershed, meaning that the differences in relation to the current land cover (dominated by shrubland) do not considerably influence hydrological services provision (Table 4.10).

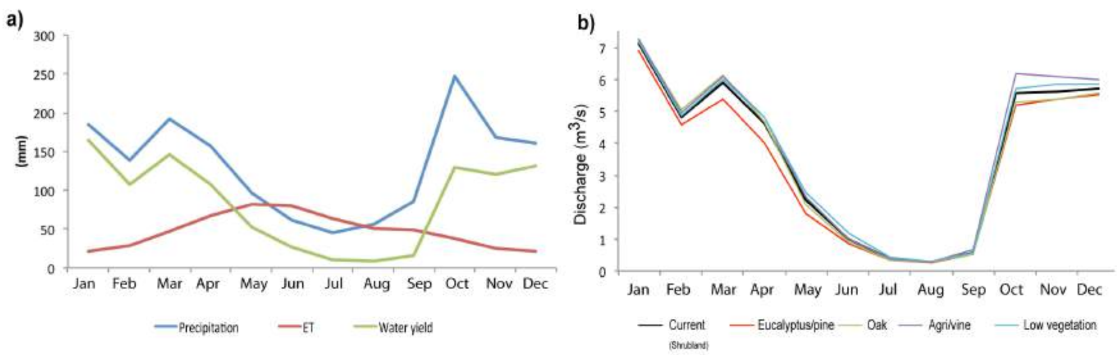

Figure 4. 4 – a) The water balance simulated by SWAT in the Vez watershed (monthly averages for the period 2003-2008); and b) average monthly discharge under different land cover scenarios (m^3/s).

Regarding the provision of water supply, a reduction in the total water yield has been found when forest area increases (1% in conservation scenario leading to oak forest, and 7% in intensification scenario involving pine and eucalypts). In contrast, there is 6% increase in the total water yield under agriculture expansion, and 3% under low vegetation scenario (Table 4.10). The reduction on the total water yields in the forestation scenarios are related to higher evapotranspiration when compared to the low vegetation and agriculture scenarios

(Table 4.10). This is in line of what is reported in the literature, although the magnitude of change is lower than the most common observations around the world (Brown et al., 2005; Farley et al., 2005). However, recent studies with modelling exercises reported very similar magnitudes of change. For instance, Morán-Tejeda et al. (2014) reported a small impact of land cover on overall water resources using SWAT in Spain. In the present study, this pattern may be explained by the high rate of precipitation, associated to a fair evaporative regime in Vez region, which combined with shallow soils masks the role of forests in the water cycle. In general, forests decrease the annual average discharge, but the degree of change is very site specific (Calder, 2000). Moreover, the Mediterranean climatic regime of this area implies that rainfall and potential evapotranspiration peaks are in opposite seasons (respectively winter and summer Figure 4.4a), resulting either in strong rainfall excesses or soil moisture deficits. In this case, differences in the water use potential of land cover would play a smaller role. In addition, the soils in the catchment are shallow, which limits the water storage capacity (ranging from 15 to 135mm), further decreasing water availability for evapotranspiration in summer, while also limiting the rooting depth of trees. These processes have been explored in similar environmental watersheds in Portugal for the apparent lack of impact of afforestation on streamflow (David et al., 1994; Hawtree et al., 2014). In any case, it should be noted that the soil water content in Vez watershed is largest in the low vegetation scenario, related with the low water demand from vegetation (Table 4.10).

Table 4. 10 - Land cover effects on hydrological services provision, simulation 2003-2008.

		Water supply quantity		**Water timing and flood mitigation**			**Water quality**			**Soil erosion control**	
Land-cover scenario	ET (mm)	Total annual water yield (mm/yr)	% change	Q5 (m^3/s)	Q95 (m^3/s)	Average soil water content (mm)	NO_3-N (mg/l)	Nº days with NO_3-N exceeding 5.6 mg/l	N exports (kg/ha.yr)	Average sediment export (t/ha.yr)	% of the basin above 0.1 t/ha.yr soil erosion
Current cover	590	1025		29.3	0.16	111	1.9	74	1.04	0.005	0
Eucalyptus /pine	660	955	- 7	28.2	0.15	111	2.1	104	1.11	0.005	0
Oak	597	1017	- 1	30	0.16	121	1.9	64	1.36	0.006	0
Agri/vine	532	1083	+ 6	31	0.17	121	2.2	68	1.44	0.045	30
Low vegetation	557	1058	+ 3	30.3	0.18	125	1.7	52	1.32	0.007	0

Considering the flow regime for water timing and flood regulation services, the flow duration curves (that show the river flow variability) indicated no significant differences between land cover scenarios (Figure 4.5a). Low flow values (Q95) were similar between land cover scenarios (Table 4.10). However, the forestation scenario with eucalyptus/pine led to a decrease in flows during summer (between -11% and -17%). Rapid growing species, such as eucalyptus, are associated to high water demands increasing the concerns of water availability in the dry periods (Garmendia et al., 2012). Although none of the scenarios led to the river drying during summer, the lower summer streamflow could still be insufficient for aquatic ecosystems or socio-economic water demands, which were not considered in this analysis. Land cover also influenced high flows (Q5), where the forest scenario of eucalyptus/pine showed the lower values for peak flows and overall flows during the wet season (Figure 4.4b). This pattern is favourable for the flood regulation service, because high flows are attenuated when forests are present (Calder & Aylward, 2006). Note that, deciduous forests, such as oak, decreased the role on flood regulation from December to May, due to the dormant period during the winter-wet season. In contrast, agri/vine scenario showed the highest peak flows, mainly when winter rainfall starts (Figure 4.4b). For example, simulations of a forest clear-cutting has caused a strong increase in peak discharge in a small watershed in Norway (Kalantari et al., 2014).

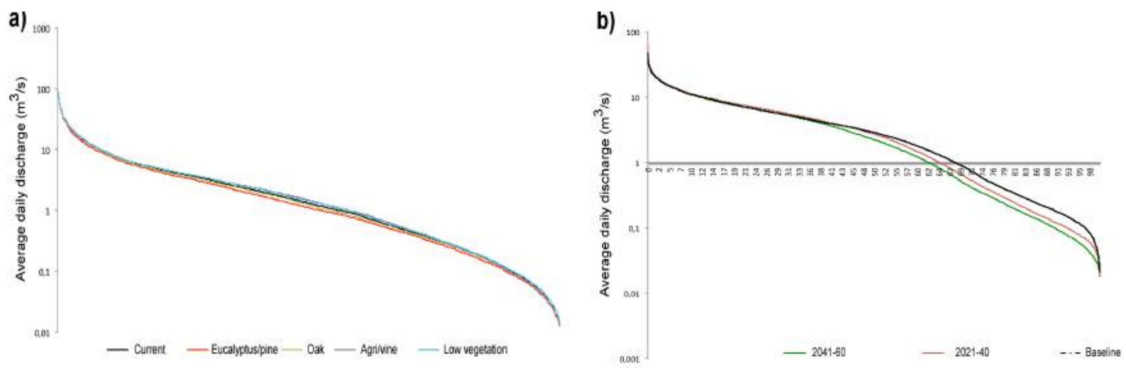

Figure 4. 5 – Flow duration curves for: (a) land cover scenarios; (b) and future climate conditions (logarithm scale). Those curves express the probability of exceeding a given streamflow.

Water quality is not presently an issue in the Vez watershed, due to the low intensity agriculture and low-density urban area, as well as the lack of wastewater discharges. Here, agri/vine is the scenario with major nitrogen (N) exports, 1.44 kg/ha.yr, and major NO_3-N concentration at the river outlet, 2.2 mg/l (Table 4.10). When comparing land covers, agricultural areas (corn and winter pasture) contribute more for N exports (9.37 kg/ha.yr) than forests (0.25 and 0.46 kg/ha.yr) (Table 4.6). In Portugal, as generally around the world, sub-catchments dominated by agricultural fertilized crops export five times more nitrates than sub-catchments covered by forests (Yevenes & Mannaerts, 2011). Remarkably, the eucalyptus/pine scenario has the most days with daily-simulated NO_3-N concentrations in the river exceeding 5.6 mg/l, established as the guideline value for standard surface water quality in Portugal (Dec 236 98, 1998). This is related with the lower discharge that reaches the river in this scenario, rather than with higher N exports.

Equally, soil erosion is not problematic in the watershed, considering that all values are far less than 1 t/ha.yr, set as tolerable rate for soil formation and good status for water quality in Europe (Verheijen et al., 2012). The low simulated values are related to the prevalence of shallow soils and bare rock. The agri/vine is the scenario with the highest sediment export rates (0.045 t/ha.yr). It is expected that scenarios of agricultural area expansion are more prone to soil erosion, especially if agriculture is practiced in steep slopes without terraces, as in the case of vineyards (Zhang et al., 2014). When considering an erosion risk threshold of 0.1 t/ha.yr, about 30 % of the area is above 0.1 t/ha.yr (Table 4.10). This lower value could be considered since shallow soils may suffer degradation from relatively low erosion rates (Bakker et al., 2005). These results concur with measurements made in central Portugal, which indicated arable land as the most important land cover for runoff and soil erosion (Nunes et al., 2011).

In general, the option for one particular land cover scenario is not expected to compromise the overall provision of hydrological services in the Vez watershed. Some scenarios can perform better a certain hydrological service provision: low vegetation for water supply, oak for water supply timing, eucalyptus/pine for flood regulation and soil erosion control and shrubland (current land cover) for soil erosion control. However, trade-offs with other services provision should be evaluated, in particular eucalyptus/pine against biodiversity conservation (Proença et al., 2010b; Onaindia et al., 2013). In conclusion, future planning options for the watershed may include forest growth for a bundle of ecosystem services provision, such as carbon storage and pulp production, without prejudice to hydrological services provision, particularly the water quantity.

4.3.3. Future climate effects on hydrological services provision

Climate signals from the downscaling bias-corrected ensemble of 4 GCM models under the RCP 4.5 medium emissions scenario are presented in Table 4.11. Results evidenced important changes that may occur in rainfall and temperature seasonality. A generalized warming is expected with temperature changes oscillating between 0.35 ºC during spring and 2.02 ºC in summer, more pronounced for maximum temperature parameter in 2041-60. During 2021-40, average annual precipitation is expected to slightly increase (1.20%), but with strong changes to variability between seasons. In fact, an important increase during winter is expected (7.88%), and higher declines during spring and summer (-14.5%). These patterns may persist during 2041-60, except for the annual precipitation that is expected to decrease 3.86%, mainly due to the high decrease during summer (-24.5%).

Table 4. 11 - Changes in precipitation, maximum and minimum temperature, in northwest Portugal, under RCP 4.5 scenario (ensemble of 4 GCMs).

	2021-40			**2041-60**		
	ΔPrec (%)	**ΔTMAX (ºC)**	**ΔTMIN (ºC)**	**ΔPrec (%)**	**ΔTMAX (ºC)**	**ΔTMIN (ºC)**
Winter (Jan – Mar)	7.88	0.83	0.39	7.75	1.33	0.83
Spring (Apr – Jun)	- 4.85	1.13	0.35	- 8. 71	1.78	0.85
Summer (Jul – Sep)	- 9.73	1.25	0.43	- 24.47	2.02	1.10
Autumn (Oct – Dez)	2.63	0.93	0.41	- 3.62	1.33	0.78
Annual	1.20	1.03	0.40	- 3.86	1.61	0.89

The potential hydrological consequences for the two periods of future climate conditions under the RCP4.5 scenario were compared with the 20 years simulation of the baseline period (1981-2000) under current land cover, using the previous calibrated conditions (Table 4.12). Total annual water yield is expected to slightly decrease by 2% for the period 2021-40 and by 7% for the period 2041-60 (Table 4.12). In Galicia, SWAT simulations also showed a decrease in annual discharge of about 6.03% and 12.68% for the B2 and A1 scenarios, respectively, but referring to a further time period (2071-2100) (Raposo et al., 2013). Effects were more remarkable at seasonal level, particularly influenced by changes in precipitation patterns, namely more rain during winter and less rain during summer (Figure 4.6a). In both periods, model results indicated that low flows would be more severe, especially in 2041-60 with a decrease of - 27% to - 38% in the summer months (Figure 4.6b). In addition, a reduction in the soil water content is expected for the two periods with current land cover (Table 4.12). This is in line with the climate projections for the Galicia region of Spain, where less annual precipitation is expected, with more concentration in autumn and winter, and drier springs and summers (Álvarez et al., 2011). Equally, the projected changes for the broader Mediterranean region under the new CMIP5 scenarios, forecast an intensification of climatic aridity, although those changes may be stronger if considering the RCP8.5 scenario (Feng et al., 2014). This implies that the changes expected for the Vez watershed could be worse if the RCP8.5 scenario would be considered. Limitations on water resources in the Vez watershed have not been an issue so far, because precipitation although seasonal, is enough to support demands for public water supply and irrigation. However, these expected changes for summer low flows raise concerns regarding a seasonal reduction in water resources, especially if it is combined with increasing irrigation requirements due to lower rainfall. Accordingly, special attention should be paid at mountains given that they are the main source of water generation for water supply downstream (García-Ruiz et al., 2011). Meanwhile, an increase in high flows for the months of November, February and April is expected (between 1% and 10%). This pattern can enhance flood risk, considering that by the end of the wet season soils are already saturated and the capacity to retain rainwater is diminished. Special attention should be given for the period 2021-40 when an increase of 10% in river discharge is expected by February (Figure 4.6b).

Regarding the water quality in the Vez watershed, SWAT simulations did not predict substantial changes under different climate change periods, but there is a tendency of increasing NO_3-N concentration in the river from the baseline to the future climate (Table 4.12). In contrary, N exports will slightly decrease, indicating the reduction in discharge as the cause of increasing NO_3-N concentration. The reductions in N exports seem to be dependent on the magnitude of runoff and vegetation biomass (Panagopoulos et al., 2011; Molina-Navarro et al., 2014). The increase in NO_3-N concentration from changing climate conditions is expected to enhance the incidences of algae bloom in the rivers and degrading water quality in general (Tong et al., 2012).

Average sediment loads will increase, especially during the period 2021-40. This is related to the increase of precipitation in winter and spring months, associated with a decline in biomass growth, which was also found in other studies (e.g. Nunes et al., 2008). The area with erosion rates above 0.1 t/ha.yr should expand under climate change conditions, particularly during 2041-60, in which 3.3% of the area is under risk of soil erosion (Table 4.12). In watersheds with similar climate, a major part of soil loss takes place in a small number of rainfall events with erosive power. In addition, soil losses at the outlet can be five times lower than the ones measured in the fields (Rodríguez-Blanco et al., 2013). The impact of climate change on erosion rates is expected to vary according to the catchment scale, type of land cover and future climate conditions, namely temperature change and rainfall events (Li et al., 2011; Nunes et al., 2013). A reduction in rainfall leads to significant decreases in runoff and erosion (Nunes et al., 2008; Zabaleta et al., 2014). On the other hand, biomass reductions associated to extreme rainfall events may increase soil erosion (Nunes et al., 2008; Li et al., 2011).

Table 4. 12 - Future climate effects under the RCP4.5 scenario for 2021-40 and 2041-60 periods, combined with two different land cover scenarios. Baseline 1981-2000.

		Water supply quantity		**Water timing and flood mitigation**			**Water quality**			**Soil erosion control**	
	ET (mm)	Total annual water yield (mm/yr)	% change (climate effect only)	Q5 (m^3/s)	Q95 (m^3/s)	Average soil water content (mm)	NO_3-N (mg/l)	Nº days with NO_3-N exceeding 5.6 mg/l	N exports (kg/ha.yr)	Average sediment export (t/ha.yr)	% of the basin above 0.1 t/ha.yr soil erosion
Baseline (current land cover)	678	2619		48	4.3	165	0.42	0	1.83	0.014	2.5
2021-40	751	2558	- 2	48.3	3.4	156	0.67	0	1.73	0.021	2.7
2041-60	750	2443	- 7	47.6	2.5	156	0.68	0	1.77	0.018	3.3
Baseline (Eucalyptus/pine)	886	2412	- 8	46.4	2.8	169	0.73	0	1.99	0.016	2.5
2021-40	919	2391	- 9 (-1)	47.3	2.3	164	0.75	0	1.99	0.017	2.1
2041-60	832	2360	- 9 (-2)	47	2.1	165	0.66	0	1.90	0.025	2.4
Baseline (Agri/vine)	717	2580	-1	48.2	4	173	0.86	2	2.38	0.088	32.5
2021-40	736	2573	- 2 (0)	49.1	3.4	170	0.88	2	2.38	0.092	34.7
2041-60	741	2451	- 6 (-5)	47	2.7	166	0.93	2	2.30	0.090	33.4

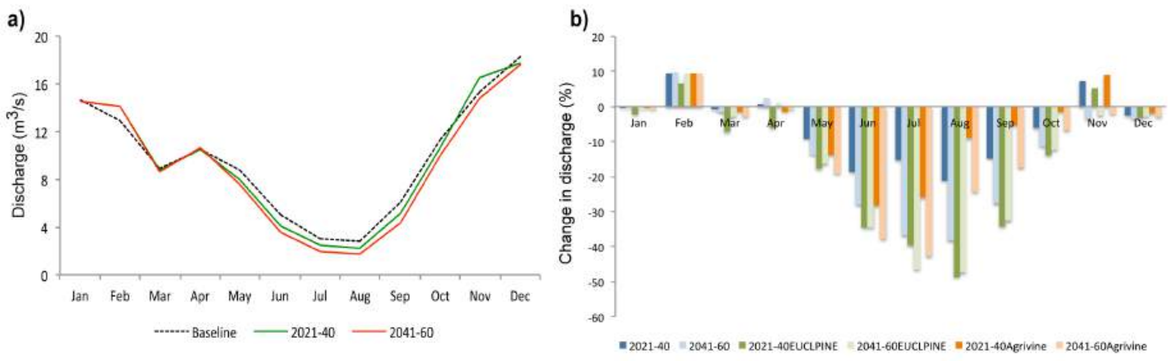

Figure 4. 6 – a) Average monthly discharge (m^3/s) under future climate conditions; and b) percentage of change in monthly average discharge under future climate conditions combined with land cover scenario of increase eucalyptus/pine forest or increase agriculture.

Overall, the provision of hydrological services, particularly the timing of water supply with incidence on drier low flows and flood mitigation, should be affected by climate change conditions under a medium emission scenario in the Vez watershed, more pronounced for 2041-60.

With this approach, a picture of changes in the provision of hydrological services under a medium emission scenario was given. Other scenarios and models could have been used, but the objective of this study was to give a medium scenario in combination with land cover. Another limitation of this study is the use of a GCM with statistical downscaling instead of dynamical downscaling by the use of a RCM (Regional Climate Model). At the moment, RCMs for the new RCP scenarios are not available, limiting the available choices for downscaling. However, the bias-correction step approximates the scenario values to the climatic patterns of the region. Moreover, the use of 20-year window instead of 30 years was imposed by the lack of observed data. Other studies have used the same time period with success (Morán-Tejeda et al., 2013; Shi et al., 2013).

4.3.4. Combined effects of land cover and future climate conditions on hydrological services provision

The combined effects between future climate conditions and land cover were assessed using climate projections and the two land cover scenarios with the most substantial results from section 4.3.2, namely the eucalyptus/pine and agri/vine scenarios. These scenarios can also be considered the most realistic for future land cover in the Vez watershed, since current policy and incentives favour eucalypts and farming expansion, due both to the fast growth of exotic tree species, and the economic benefits associated with plantation forestry and farm expansion. The model results for the combined scenarios were then compared to the baseline climate (1981-2000) with current land cover (shrubland dominated).

The combined effects of climate and land cover change can both enhance or degrade hydrological services provision, depending on the type of service and of land cover scenario (Table 4.12). Both land cover scenarios showed a reduction in the total annual water yield under future climate conditions, more pronounced with eucalyptus/pine scenario with a reduction of 9%, when compared to the baseline climate and land cover. However, if only climate change is considered, the reduction is between -1 and -2%, indicating that the effect of forest cover in the total annual water yield is more important than the climate effect. The reduction in the total water yield is less visible in the agri/vine scenario, and a small synergetic effect is shown in 2041-60. This tendency of reduction is contradictory with the findings from section 4.3.2, in which agriculture increases water quantity. An increase in temperature might improve growing conditions for vineyard in the winter-wet season, therefore increasing the water use (Nunes & Seixas, 2011).

Low flows decrease with the eucalyptus/pine scenario for both periods, especially in the summer months of July and August with changes of about -50% when comparing to the baseline (Figure 4.5b). Again, the effect of land cover is more visible than the climate effect. The low flows in agri/vine scenario are similar to the current land cover (Table 4.12). On the other hand, high flows (Q5 Table 4.12) are slightly reduced by climate change combined with the eucalyptus/pine scenario, especially in winter and beginning of spring. This means that forestation could have a positive role in mitigating the peak flows, particularly in 2021-40 (Figure 4.5b). In contrast, high flows are slightly exacerbated with the agri/vine scenario (Table 4.12).

Regarding water quality, an increase in NO_3-N concentrations and a reduction in N exports are expected for future climate, as it was described in section 4.3.3. This tendency is aggravated under the agri/vine scenario, which showed the greatest NO_3-N concentrations and N exports, especially in 2041-2060 (Table 4.12). In fact, nutrient loads are very sensitive to land cover change, since it introduces different quantities of fertilization and organic matter (Panagopoulos et al., 2011). The evaluations of the daily-simulated NO_3-N concentrations in the river never exceeded the value of 5.6 mg/l, with exception of 2 days under the agri/vine scenario. Nevertheless, low flows may be aggravated if a different scenario of climate change is considered (e.g. RCP 8.5), which could surpass this water quality threshold value, especially when associated to agri/vine scenario.

Soil erosion should be higher when climate is combined with the agri/vine scenario, particularly in 2021-40 when there is more precipitation during winter (Table 4.12). The area suffering erosion rates above a tolerable value grows considerably in agri/vine scenario

(2021-40: 34.7% and 2041-60: 33.4%), when compared to eucalyptus/pine and current land cover.

Overall, the combined effects of climate and land-cover seem to aggravate the decline in annual runoff from climate change in the eucalyptus/pine scenario (- 9%), with further reductions in the low flows during summer months (-32%; -49%). However, this scenario shows a synergetic effect on peak flows reduction and soil erosion control. This is consistent with tendencies reported in recent studies across the Mediterranean basins using combined effects of climate and re-vegetation scenarios (López-Moreno et al., 2013; Morán-Tejeda et al., 2013). For the agri/vine scenario with future climate conditions, the area under erosion risk should increase, together with a degradation of the water quality (increase in NO_3-N concentration).

It should be noted that the negative implications of the combined effects on hydrological services provision must be put in perspective, especially by also taking into account the demand side of services. A trade-off analysis between a given service provision with land cover, climate effects and service demand should be evaluated for an integrated analysis, considering flexible strategies for water management at a watershed scale.

5. Conclusion

SWAT was applied to a medium-sized watershed in northwest Portugal, calibrated and validated against daily discharge, with good agreements between model predictions and field observations. Given the limitation of observed data, calibration of sediments and nitrates can be considered valid, strengthen by a comparison with values from literature in similar regions.

The hydrological consequences of four different land cover scenarios were compared to the current land cover scenario. Different land cover options would not compromise the overall provision of hydrological services, but some scenarios can be assigned specifically to improve a certain hydrological service provision. For instance, allowing natural vegetation to recover (oak forest) would lead to a more regular distribution of water flows throughout the year, or allowing forest of eucalyptus/pine would reduce peak flows and soil erosion during winter.

A statistical downscaling of four GCMs models, bias-corrected with ground observations was done for the period 2021-40 and 2041-60, using the RCP4.5 medium emission scenario. Results show an increase in temperature ranging from 0.32ºC in spring (2021-40), and 2.0ºC in summer (2041-60). Combined with a decrease in precipitation (-3.9%), which is more pronounced in summer (-25%) for the period 2041-60. Although climate change has slightly less effect in reducing total annual water yield, when compared to land cover, the effect of climate change is significantly higher in further reducing the low flows in summer and increasing soil erosion in winter. The combined effects of climate and land cover change can both enhance or degrade hydrological services provision. The decline in annual runoff from climate change will be aggravated in the eucalyptus/pine scenario, with special emphasis in further reducing the low flows in summer (-16% in 2021-60; and -40% in 2041-60). In turn, peak flows and soil erosion will be attenuated. On the other hand, annual runoff will be offset with agri/vine scenario, but soil erosion will be highly aggravated.

Results emphasize the importance of building adaptation strategies that consider both climate and land cover changes, with special attention for water supply timing during summer, peak flows and soil erosion during winter.

Acknowledgments

This study was financially supported by FCT (Portuguese Science Foundation), and the European Social Fund through Ph.D grant SFRH/BD/66260/2009 to C. Carvalho-Santos, and post-doctoral grant to J.P. Nunes (SFRH/BPD/87571/2012). Antonio T. Monteiro was supported by the project “Biodiversity, Ecology and Global Change” co-financed by North Portugal Regional Operational Programme 2007/2013 (ON.2 – O Novo Norte), under the National Strategic Reference Framework (NSRF), through the European Regional Development Fund (ERDF). J. Honrado received financial support from Programa Operacional Fatores de Competitividade (COMPETE/FEDER) and the Portuguese Government / Fundação para a Ciência e a Tecnologia (FCT), through Project Grant PTDC/AAG-MAA/4539/2012 (“IND_CHANGE”). The authors would like to thank Joaquim Alonso, IPVC Ponte de Lima, for providing land use and soil maps; João Gonçalves, CIBIO University of Porto, for providing DEM; and Isabel Poças for providing MOD16A2 ET product from MODIS.

Chapter 5

From hydrological services to a multifunctional watershed: trade-offs and synergies between biodiversity conservation and forest ecosystem services

Abstract
Ensuring forest protection and the delivery of forest ecosystem services is one of the aims from the European Union biodiversity strategy to 2020. Therefore, accurate modelling and mapping of both ecosystem services and biodiversity conservation value is an important effort to support spatial planning and land management options involving forest and ecosystems. In this context, the objectives of this study are: to analyse the provision and dynamics of the multiple ecosystem services under two forest cover change scenarios (oak and eucalyptus/pine) compared to the current scenario of shrubland dominated, at the watershed scale; and to evaluate their possible trade-offs with the biodiversity conservation value. The Vez watershed, in northwest Portugal, was used as case-study area, in which SWAT (Soil and Water Assessment Tool) was applied to simulate the provision of hydrological services (water supply quantity, timing and quality, soil erosion, and flood regulation), as well as biomass and carbon storage services. Biodiversity conservation value was based on nature protection regimes and on expert judgement applied to a land cover map. Results indicated that the current delivery of ecosystem services is higher in the high and low mountain sub-basins, and lower in the valley sub-basin. The overall performance for water quantity and timing is better under the shrubland and oak forest scenarios, when compared to the eucalyptus/pine forest scenario. In turn, the latter has better performance for the provision of flood regulation and erosion control services, especially in the low mountain sub-basin. The current shrubland dominated cover also shows good performance for the control of soil erosion. The oak scenario is the one with less trade-offs between forest services and biodiversity conservation. Even if water quantity is currently not a problem in the Vez watershed and that eucalyptus/pine is the scenario with better results for flood regulation, caution should be taken with this scenario due to its effects on biodiversity conservation and likely also on fire hazard. Results highlight SWAT as an effective tool for modelling and mapping ecosystem services generated at the watershed scale, therefore contributing to improve the options for land management and governance.

Keywords: Biodiversity conservation; Ecosystem services; Forests; Land cover scenarios; SWAT; Vez watershed.

Carvalho-Santos C., Silva A.R., Gonçalves J., Honrado J. (submitted) From hydrological services to a multifunctional watershed: trade-offs and synergies between biodiversity conservation and forest ecosystem services.

5.1. Introduction

Watersheds are considered primary units for ecosystem services management and planning (Panagopoulos et al., 2011; Cook & Spray, 2012; Boithias et al., 2014). Forests and forestation are used as a management strategy to improve ecosystem services provision in many watershed around the world (Lele, 2009; Quintero et al., 2009; Onaindia et al., 2013). Financial mechanisms are supporting several forestation actions, either by forest subsidies under agri-environmental schemes, for instance in Europe, or by payments for ecosystem services, mainly applied in tropical countries (Hein et al., 2013).

Furthermore, ensuring forest protection and the delivery of forest ecosystem services is one of the aims inscribed in the EU Biodiversity Strategy to 2020 (EU, 2011). However, land cover and land use changes pose major challenges to water resources management and the provision of hydrological services (Kepner et al., 2012; Geneletti, 2013). Therefore, understanding the processes behind forest ecosystem services provision as well as their trade-offs with biodiversity conservation is a useful asset to support spatial planning and land management. In addition, several studies have shown that mapping ecosystem services can be highly useful for informing land-use and management decisions on trade-offs and win-win situations between ecosystem services (Chan et al., 2006; Egoh et al., 2008; 2009; Nelson et al., 2009).

Beyond the traditional source of timber and pulp, forests have long been known for providing other services for human well-being, such as carbon sequestration and hydrological services (water supply and water damage mitigation) (Shvidenko et al., 2005; Brauman et al., 2007; Carvalho-Santos et al., 2013). Although the overall balance of forests on services provision is generally positive, their influence on the hydrological processes is complex and often site specific, requiring daily rainfall-runoff modelling for an accurate evaluation (Calder, 2002; Malmer et al., 2010; Crossman et al., 2013). This is especially important regarding the magnitude of decreasing the total annual water yield in the watershed (Bosch & Hewlett, 1982; Brown et al., 2005). In fact, forest plantations are encouraged for carbon sequestration strategies, but the environmental consequences of forestation are often not fully considered, for instance, on the reduction in annual streamflow (Jackson, 2005).

After acknowledging the role of forests on hydrological services provision in a given watershed, further analysis can be performed to evaluate the provision of other services (Logsdon & Chaubey, 2013). SWAT (Soil and Water Assessment Tool) is a hydrological modelling tool applied worldwide for the evaluation of the hydrological regime in a watershed (Arnold et al., 1998). Ultimately, the SWAT outputs can also be used to model the provision of other non-hydrological services, such as carbon sequestration and timber production (Logsdon & Chaubey, 2013). Also, the option for different land covers and landscape configurations may induce trade-offs between the provision of multiple ecosystem services and biodiversity conservation (Chisholm, 2010; Villamagna et al., 2013; Wang & Fu, 2013). In this context, modelling and mapping those trade-offs is an important step to create sustainable options for forest management (Ninan & Inoue, 2013; Onaindia et al., 2013; Wang & Fu, 2013).

The purpose of this study is to map the provision of multiple ecosystem services at the watershed level, using SWAT as the primary modelling tool, and to evaluate their possible trade-offs with biodiversity conservation based on habitat value and protection regimes. These trade-offs were analysed dynamically by comparing forest services provision and the biodiversity conservation value under two distinct forestation scenarios (eucalyptus/pine vs. common oak) compared to the present condition dominated by shrubland. The watershed level of analysis is particularly interesting here, because it constitutes the base unit when all the processes operate, namely the flow of water (Savenije & Van der Zaag, 2008). The research was developed following a four-stage workflow. First, the modelling and mapping of the ecosystem services and biodiversity conservation was developed. Subsequently, the spatial distribution of the ecosystem services and biodiversity conservation value was analysed under the forestation scenarios described before. Then, a spatial correlation was performed to analyse the conflicts or synergies between the provision of ecosystem services and biodiversity conservation. Finally, the results were analysed and discussed in a governance framework, particularly to support land management options for improving the decision-making processes for ecosystem services provision and biodiversity protection.

5.2. Methodology

5.2.1. Study-area

The study area was the watershed of river Vez, a medium-sized watershed (252 Km^2) located in the Soajo and Peneda mountains, northwest Portugal (Figure 5.1). The Vez is one of the main tributaries of river Lima, a major river in northwest Iberian Peninsula. Annual precipitation in the watershed varies from 1000 mm/year in lowlands up to 3000 mm/year in highlands (wet years), mainly concentrated in the autumn and winter months (October to March). Topography is complex with elevation ranging from 30 m to 1400 m, and slopes above 25% shaping 58% of the watershed. Granites and locally schist characterize the regional geology, with five major soil types occurring in the watershed: Humic Regosols (67%) and Leptosols (9%) prevail in highlands: Dystric Antrosols (22%), Fluvisols (1%) and Urban (0.56%) in lowlands. Regarding land cover/use, open areas of bare rock and heath occupy the top of the mountains, shrurbland with scattered woodland areas occupy the highlands, and agricultural land associated with forest areas of European oak (*Quercus robur*), Maritime pine (*Pinus pinaster*), and Eucalypts *(Eucalyptus globulus)* are common in lowlands (Figure 5.2a). Approximately one third of the watershed (the mountainous areas and the river Vez itself) is included in the EU Natura 2000 network, and the upper part of the watershed is further included in the Peneda-Gerês National Park (Figure 5.2b). These areas are very important for biodiversity conservation, with the presence of some charismatic species such as the iberian wolf

(*Canis lupus signatus*), roe deer (*Capreolus capreolus*) and several birds of prey. Phytogeographically the region represents the southwest limit of the Eurosiberian (Atlantic) region, with sub-Mediterranean, deciduous oak forests as the potential vegetation type (Costa et al., 1998; Capelo et al., 2007).

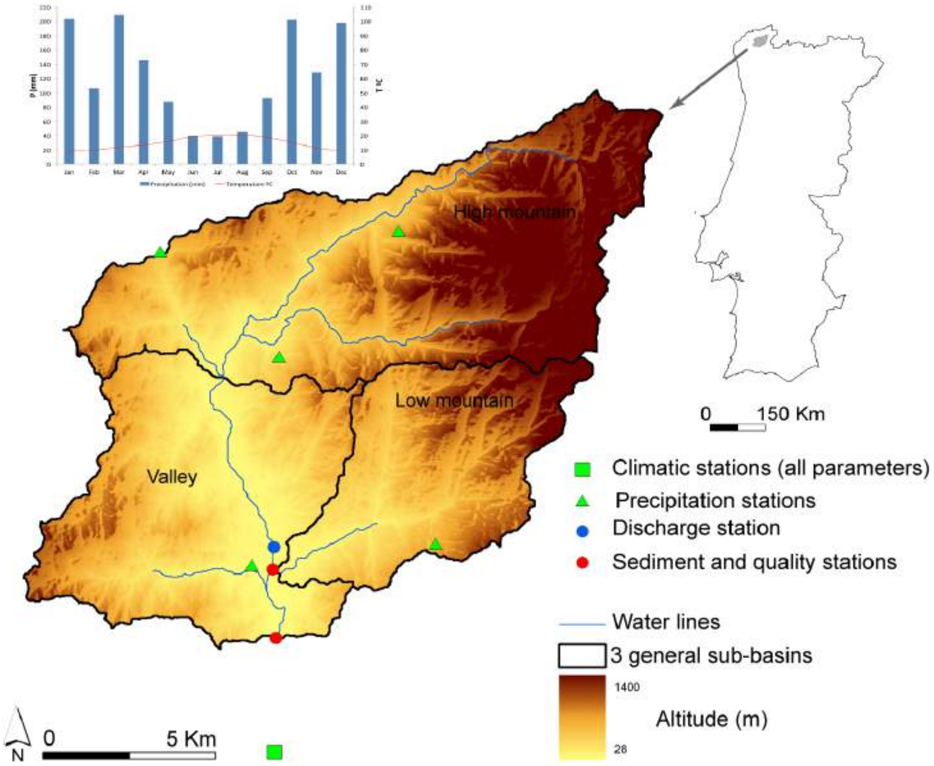

Figure 5. 1 – The study area, Vez watershed, with the location of observed data stations used to setup SWAT model, the range of altitude and a climate plot (yearly average values 1999-2008).

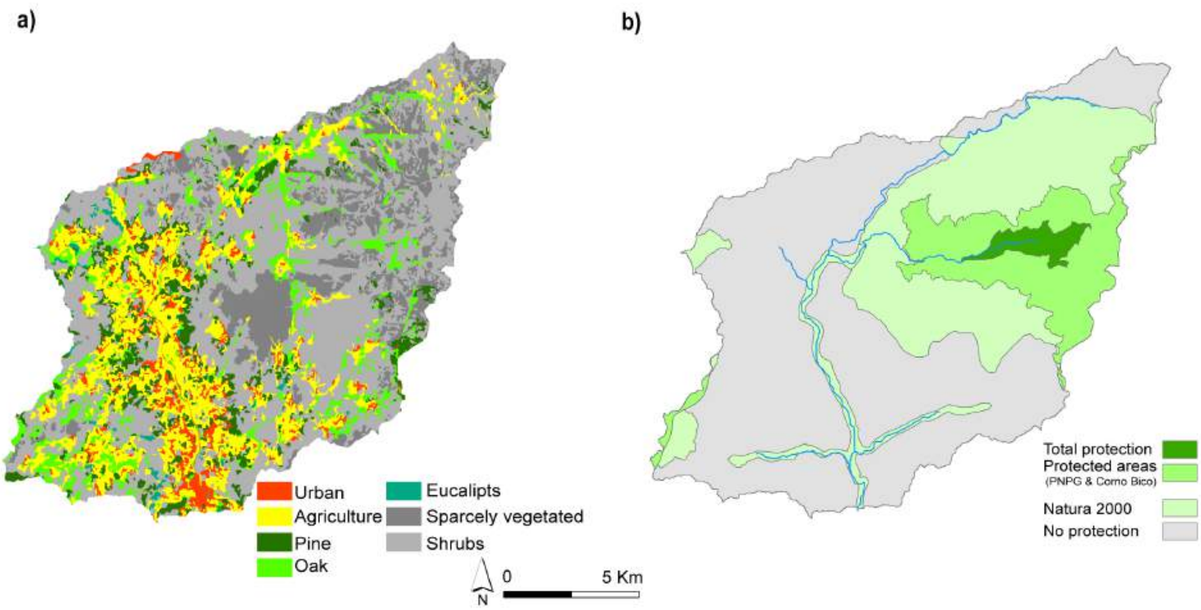

Figure 5. 2 – a) Land cover map of Vez watershed (year 2006); b) Biodiversity protection levels in the Vez watershed.

5.2.2. Assessment of ecosystem services provision

5.2.2.1. Hydrological services

Hydrological services encompass the benefits for people involving water in the ecosystems (Brauman et al., 2007). Following the conceptualization used in a previous study (Carvalho-Santos et al., 2013), the provision of water supply (quantity, timing and quality) and water damage mitigation (flood mitigation and erosion control) were considered for modelling and mapping in the Vez watershed. The accuracy of the hydrological services modelling improves when using daily-runoff models, such as SWAT (Crossman et al., 2013). SWAT is a deterministic, physically-based and semi-distributed hydrological model used successfully around the world (Arnold & Fohrer, 2005). The watershed is first divided into sub-basins, and after each sub-basin is divided into HRUs (hydrologic response units), which are land areas of varying size, but with the same land cover, soil type and slope class (Gassman et al., 2007). These units are spatially explicit and provide different contributions to the provision of hydrological services. However, SWAT is not a completely distributed model, meaning that inside a given sub-basin, such unique combination of land cover, soil type and slope (HRU) can be found in different not adjacent places. The hydrological contribution of the several areas belonging to a given HRU is considered the same. The use of HRUs and the analysis of their contribution for services provision converges with the ecosystem services providing units (Esp) concept used for ecosystem services analysis and evaluations (Rounsevell et al., 2010).

SWAT was applied in the Vez watershed and detailed description of the model setup and parameterization can be found in the previous chapter 4. Here, the watershed was divided into 10 sub-basins with a total of 500 HRUs (320 HRUs for oak and eucalyptus/pine scenario), based on land cover, soil types and slope classes. SWAT was forced with daily climatic data for the watershed (precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed) (Table 4.3). Finally, a calibration exercise was performed, in which some parameters were adjusted in order to achieve the best approximation to the reality. A good agreement between model predictions and field observations related with discharge was obtained (Figure 4.2). A comparison between observed sediments and nitrates (NO_3) exports as well as with the values presented in the literature was made against SWAT simulated values. Overall, this calibration can be considered adequate given the limitations of observed data (Figure 4.3).

The model outputs were analysed at the HRU and sub-basin level, and adapted to each service provision (Table 5.1). Three major sub-basins were used here to facilitate the spatial description of the service provision inside the watershed: high mountain, low mountain and valley (Figure 5.1). As the outputs from water quality, soil erosion control and flood mitigation services do not have a direct reading (i.e. higher values correspond to lower contributions for service provision) there are no units in the respective maps in Figure 5.4. To homogenise the maps interpretation, 1 was divided by the values, allowing the HRU with more sediment exports, for instance, to have the lowest value for the erosion control service.

Table 5. 1 – SWAT indicators for ecosystem services provision analysis used in the Vez watershed

Ecosystem Service	SWAT outputs (HRU)	Indicators for service provision (rationale)
Water supply		
Quantity	WYLD - Water yield (mm)	Contribution of each HRU in delivering water for the stream.
Timing	SW_END - Soil water content (mm)	Amount of water in the soil profile, indicating soil storing capacity and water available for use.
Quality	Total nitrates (N kg/ha. yr) (sum of: ORGP; NSURQ; NLATQ; NO3GW)	The lower the exports, the higher contribution to the water quality (1/total nitrates).
Water damage mitigation		
Soil erosion control	SYLD - Sediment exports (t/ha. yr)	The higher the exports, the lower contribution to the soil erosion control service (1/ SYLD).
Flood regulation	SURQ_GEN - Surface runoff (mm)	Flash floods are mainly generated by the surface runoff. The lower the surface runoff, the higher the contribution (1/ SURQ_GEN).
Biomass production	BIOM - Total biomass (t/ha.yr)	Aboveground and roots biomass reported as dry weight.
Carbon storage (climate regulation)	Fraction of total biomass (tC/ha.yr)	Carbon stored in vegetation as a fraction of 50% of dry matter.

5.2.2.2. Biomass production and carbon storage

Biomass production is a proxy indicator for the provisioning services, according to the underlying land cover, (i.e. timber production in forest patches, pasture for grazing in shrublands patches, and food/fodder in agricultural land). Carbon storage is a proxy indicator of the climate regulation service, considering that forests and other stable vegetation types (e.g. shrublands) storage, on average, 50% of their dry biomass as carbon (Paladinic et al., 2009; Olschewski et al., 2010). Biomass is thus the baseline indicator to calculate carbon storage and used in many studies (Nelson et al., 2009; Crossman et al., 2013). SWAT has a vegetation growth model incorporated, which interacts with evapotranspiration considering plant phenological development, leaf growth and light interception to produce biomass during the simulation period (Neitsch et al., 2011). In this study, the SWAT biomass output (t/ha) at the HRU level was used to map the biomass production service, which serves as proxy indicator for pulp production in the eucalypt patches, wood for pine and oak patches, and fodder in agricultural and shrubland patches.

Carbon storage (tC/ha) was calculated as a fraction of 0.50 of the SWAT biomass output, for vegetated land cover classes (forest, shrub, and agriculture) (Olschewski et al., 2010). In the literature, there are different carbon fractions reported for forest types (e.g. pine = 0.51; eucalyptus and oak = 0.48) (Pereira et al., 2010). Nevertheless, as the difference is negligible and for simplicity the fraction of 0.50 was applied to all land covers. Only the carbon stored in the vegetation (above and bellow ground pools) was considered, since there was no available data to calculate the other carbon pools (e.g. soil organic matter). Forests are known for being important ecosystems for carbon sink, since they maintain a growing biomass for many decades, in the case of no disturbance (deforestation, fire, pests) (Shvidenko et al., 2005; Deal et al., 2012). Carbon fraction in the biomass varies according to the environmental conditions of each region, the different tree species, and increases with the age of trees or stands. In this study, the biomass value used was an annual average for the simulation period.

5.2.3. Assessment of biodiversity conservation value

Biodiversity enhances the ability of ecosystems to maintain multiple functions, such as carbon storage, productivity or pollination (EASAC, 2009; Elmqvist et al., 2009; Maestre et al., 2012). However, different land cover options may induce trade-offs or synergies between the provision of goods and services, and the conservation of biodiversity (Egoh et al., 2009; Onaindia et al., 2013). Therefore, an evaluation of multiple ecosystem services is most relevant if considered together with the mapping of biodiversity conservation value (Nelson et al., 2009). In this study, the biodiversity conservation value was computed based on the average, intrinsic value of each land cover/habitat type and on the presence of several nature conservation or protection statutes. The conservation value of each land cover type was mapped based on a previous study in the region (Honrado & Vieira, 2009), in a mountain area with similar characteristics to the Vez watershed. A total biodiversity conservation value was attributed to each land cover class, resulting from the sum of the values for the conservation of several terrestrial biodiversity groups (see Appendix C – Table C.1). These values ranged from 1 (indicating low value) to 5 (indicating high value) and were attributed by regional experts of each taxonomic group, considering previous studies, GIS analysis of pre-existing data, and the relevant literature.

Finally, the average intrinsic value for biodiversity conservation of each land cover class was weighed according to a factor of nature protection (Figure 5.2b). Weighting values ranged from 1 (no protection regime) to 2 (according to the increasing level of protection; see Table C.1). Protection classes were defined as follows: i) areas included in the Natura 2000 network (1.5); ii) areas of Natura 2000 belonging also to the national network of protected areas (Peneda-Gerês National Park and Corno do Bico Protected Landscape) (factor 1.75); and iii) areas classified as of total protection inside the National Park (factor 2).

5.2.4. Spatial analyses

Since forestation actions are known as an effective management option to improve ecosystem services in general, two forestation scenarios (eucalyptus/pine and oak) were simulated in SWAT and compared with the current land cover of shrubland dominated (Table 5.2). The maps for these two scenarios were obtained by changing the attributes of the already land cover map of year 2006 (SIGN II, 2008). The modelling and mapping exercise, was developed as described in the previous sections using the SWAT hydrological model with ArcSWAT interface (Olivera et al., 2006), and ArcGis from ESRI. The maps for each service under the different scenarios were produced at the HRU level and classified in five classes using the same ranking for each scenario. The maps considered the contribution of each HRU for a given service provision (Figure 5.5). Besides the mapping exercise, an analysis of a statistical measure (average or median of the distribution) was performed as a complement to evaluate which scenario is recommended for a given service provision. Further statistical calculations for the spatial analysis were performed in R statistical software (R Core Team, 2014). For comparing the seven ecosystem services for each scenario, considering the whole watershed, the average values were weighted by the area of each HRU. This was accomplished by multiplying ES values by the log10 of the respective HRU area, thus weighting the area effect. The logarithm transformation of HRU areas allowed standardizing the effect of very large areas. Boxplots were used to represent the distribution of each variable by scenario (see Appendix C – Figure C.1). The Wilcoxon signed-rank test (Hollander and Wolfe, 1999) was used to analyse pairwise differences between scenarios. This non-parametric statistical hypothesis test allows comparing two paired samples when it is not possible to assume a normal distribution. Here, it is assumed data are paired and coming from the same sample. The hypothesis tested was that the outcomes of the several scenarios were different among each other. The plots in Figure 5.5 describe, in spatial statistical terms, which scenario performs better for the respective service provision, with a complemented analysis presented in Appendix C, Figure C.1.

Finally, to assess the spatial trade-offs between biodiversity conservation and ecosystem services provision, under different land cover scenarios (Table 5.2), a statistical correlation was calculated, using the Spearman rank correlation (Table 5.3) (Maritz, 1995). This non-parametric measure of statistical dependence between two variables was used here to inspect positive or negative correlations in the spatial intersection of biodiversity conservation value and ecosystem services provision. The biodiversity conservation value was computed as described above, considering the land cover map for each scenario.

Table 5. 2 - Land cover scenarios considered for SWAT simulation period 2003-2008. Urban, CORN and BSVG areas (4%) are constant.

% Land cover	**Shrub** (Current)	**Eucalyptus/pine** Intensification	**Oak** Conservation
CORN	18.7	18.7	18.7
PINE/EUCL	8	**63.5**	-
OAK	8.7	-	**63.5**
BSVG	13.8	13.8	13.8
MIGS	47.2	-	-
VINE	-	-	-

5.3. Results

5.3.1. Current patterns of ecosystem services provision

Under current land cover, with shrubland as the dominant land cover in non-agricultural landscapes, the valley sub-basin is the one with the lowest contribution for ecosystem services provision in the Vez watershed, except for water quantity (Figure 5.3). In the valley, the low provision of soil erosion control and water quality services is related to the high concentration of agricultural land in this part of the watershed.

The high mountain is the sub-basin with the most balanced provision of all the services (Figure 5.3), yielding the highest contribution for the provision of water quantity, biomass and carbon storage (note that the latter two services have the same pattern of provision because the SWAT indicator is the same, BIOM – see Table 5.1). Given the high humidity in the upper Vez watershed, large and dense shrubland areas (scrub and heath) occupy the high mountain areas, with high potential for grazing biomass production and carbon storage. Here, the high water quantity is associated with the high rates of precipitation and the lower water demand from shrubland compared with other land cover types.

In turn, the low mountain sub-basin has the best performance for erosion control, flood regulation and water quality services provision (Figure 5.3). This area includes patches of oak and pine forest associated to more gentle slopes, which decreases surface runoff therefore, contributing to the erosion control and flood regulation services.

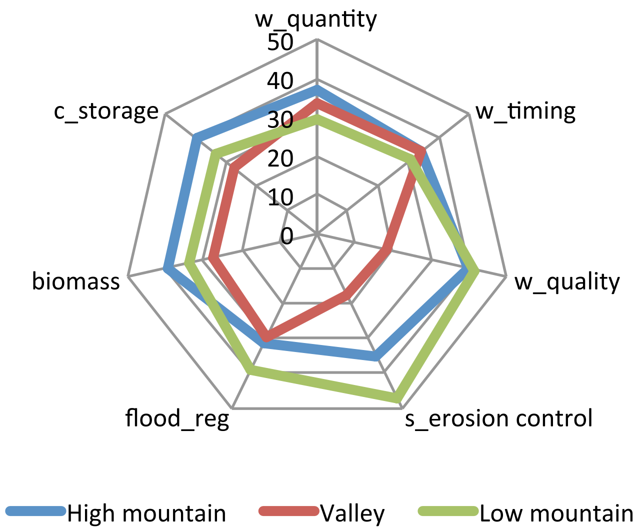

Figure 5. 3 – Ecosystem services provision by the major sub-basins (% of the service in the whole watershed). The values were weighted by the area of each HRU and by the area of the basin.

5.3.2. Current patterns of biodiversity conservation value

Regarding the current distribution of the biodiversity conservation value, the higher values are located in the high mountain sub-basin, which largely coincides with the Natura 2000 network and the National Park (Figure 5.4a). The highest values correspond to patches of common oak forest in the total protection zone (Figure 5.2b and Figure 5.4a). The low mountain sub-basin presents a fair distribution of low and high values, with the latter coinciding with Natura 2000 areas. The valley sub-basin, where the majority of the villages and agricultural areas are located, presents the lowest biodiversity conservation value overall. The exception in the extreme southwest, where there is some coverage of common oak woodland, partially included in Natura 2000 areas.

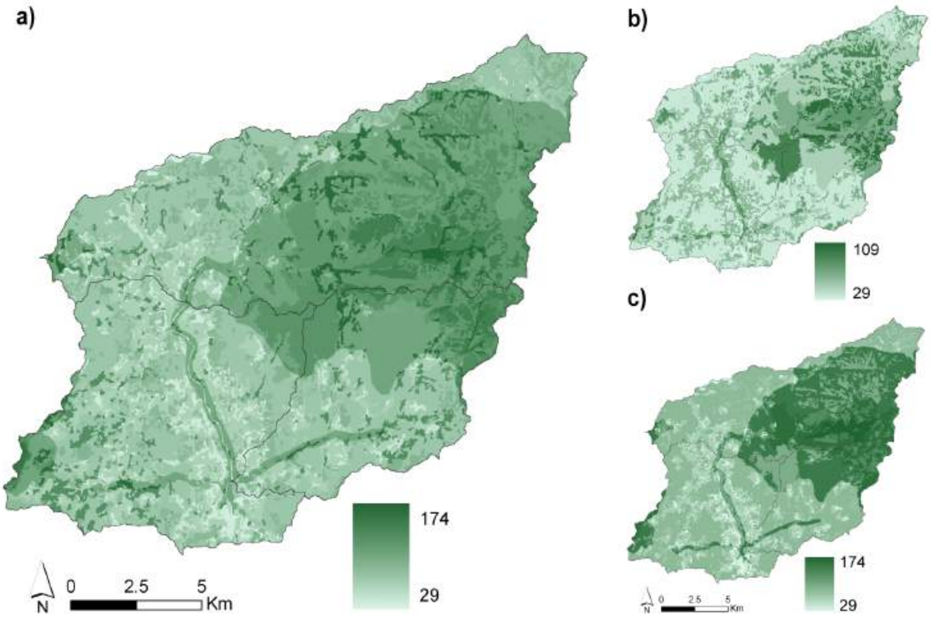

Figure 5. 4 – Spatial distribution of biodiversity conservation value in the Vez watershed; a) current pattern; b) future pattern under eucalyptus/pine scenario; c) future pattern under oak scenario.

5.3.3. Ecosystem services under land cover change scenarios

In the Vez watershed, the several services would be affected differently by the implementation of land cover scenarios (Figure 5.5; see also Figure C.1). The current shrubland situation and oak scenario would have the best performance for the water supply service (quantity, timing and quality), as well as for biomass production and carbon storage. Conversely, the eucalyptus/pine scenario would have the best performance for the water mitigation services, namely soil erosion control and flood regulation.

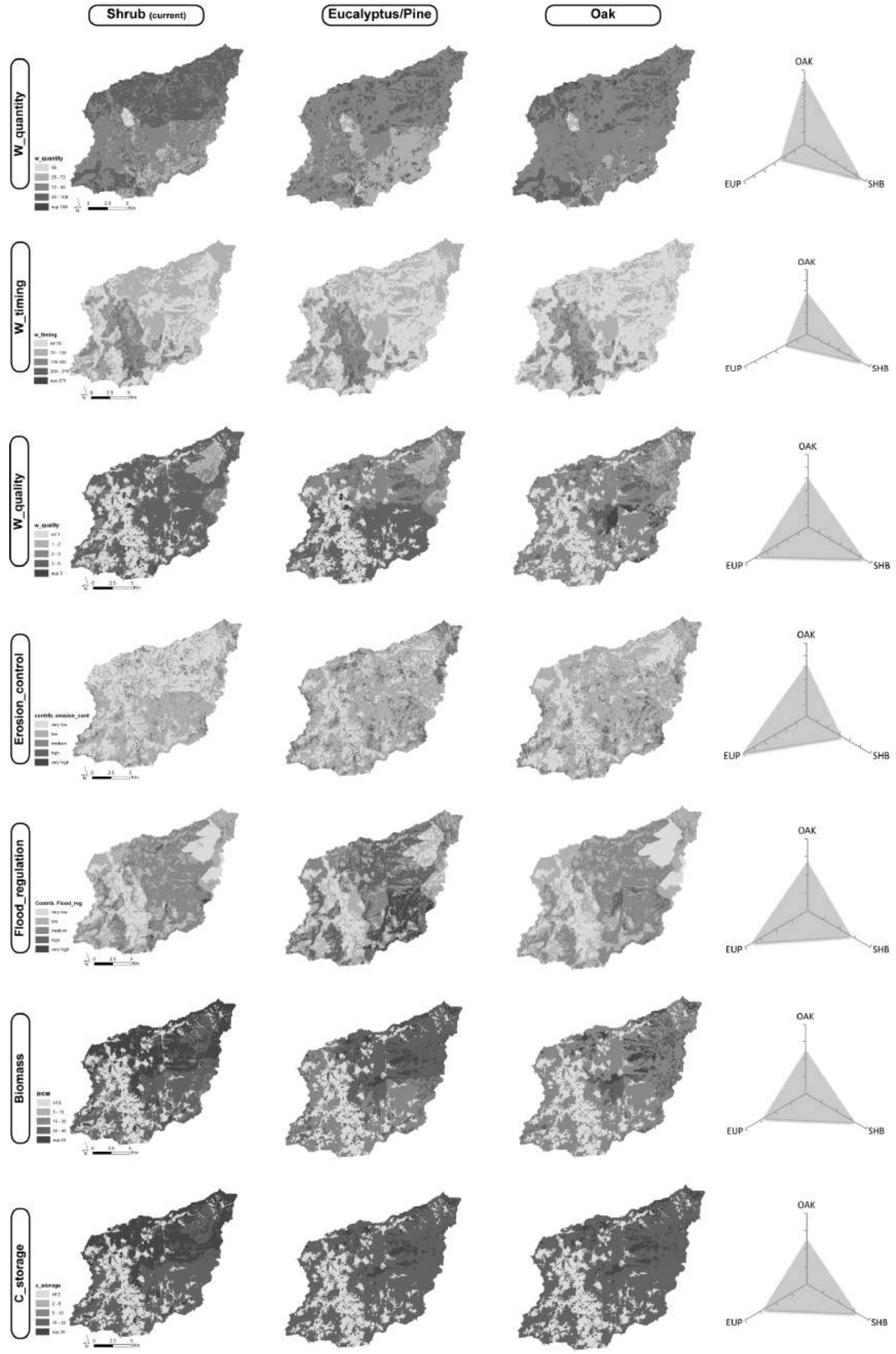

Figure 5. 5 – Maps of the ecosystem services simulated in SWAT at the HRU level, under three land cover scenarios in the Vez watershed. Plots showing the performance for the provision of each ecosystem service by the different scenarios, based on the average values for the basin, weighted by the area of each HRU (SHB – shrubland; OAK – oak; EUP – eucalyptus/pine).

5.3.4. Conservation value under alternative land cover scenarios and trade-offs with ecosystem services

The conservation value for biodiversity in the Vez watershed would decrease dramatically under the eucalyptus/pine scenario (Figure 5.4b), but it would increase in the oak scenario (Figure 5.4c) when compared to the current shrubland dominated landscape (Figure 5.4a). In the latter, conservation value has a negative or low spatial correlation with most ecosystem services, with water quantity as the only exception with a high correlation (Table 5.3). Oak scenario has the strongest positive correlations with biodiversity conservation value, except for water quantity and timing. Conversely, implementing the eucalypt/pine scenario would hold advantages for several services (such as erosion control or flood regulation), but at the expense of strong negative effects on biodiversity conservation (Figure 5.4 and Table 5.3).

Table 5. 3 - Spearman correlation test between the services provision and biodiversity conservation value, in the three land covers.

Services	Shrub	Eucalyptus/pine	Oak
W_quantity	0.18	**0.58**	- 0.06 (ns)
W_timing	- **0.26** (ns)	- 0.05 (ns)	**- 0.22**
W_quality	0.09	- **0.25**	**0.34**
S_erosion_contol	**0.14**	**- 0.38**	**0.50**
Flood_reg	**0.11**	- **0.33**	0.08 (ns)
Biomass	**0.17**	0.07 (ns)	**0.41**
C_storage	**0.17**	0.07 (ns)	**0.41**

All the analysis were statistical significant with p-value < 0.0001, with exception of the ones identified with (ns – non significant)

5.4. Discussion

5.4.1. Land cover and ecosystem services in the Vez watershed

Mapping ecosystem services at the watershed scale, which includes identifying the areas where the provision of a certain service needs to be improved, is an important communication tool and essential for proper management (Hauck et al., 2013). In the Vez watershed, the high mountain sub-basin is the one where the water quantity service is currently provided at the highest levels (Figure 5.5). This pattern is due to the high values of rainfall in the mountain, associated to the water use efficiency of the dominant shrubland vegetation. The oak forestation scenario also exhibits good performance for water quantity, especially if considering the median of the HRU values distribution (Appendix C.1). This is related to the fact that oaks are in dormant state during winter months, decreasing rain interception and transpiration fluxes, allowing water to either infiltrate or run to the rivers as surface runoff (Rosenqvist et al., 2010). In turn, the eucalyptus/pine scenario is the most unfavourable for the water quantity service. This tendency is observed in several studies, for instance in several watersheds of northern Spain, in which exotic species are negatively correlated with water yield (Garmendia et al., 2012). The same pattern applies to the water timing service, although here the most important explaining factor is the soil depth and texture associated to high vegetation cover, which improves water storage capacity and infiltration rates (Li, 2004;

Ilstedt et al., 2007). The best provision for the water timing takes place at the valley and low mountain sub-basins, due to the presence of deeper soils. In the Vez watershed, water scarcity has not been a problem, even in summer where normally rainfall is scarce and plants need to use water from soil moisture.

Nonetheless, different land management strategies should be considered according to their effects on the water quantity and timing especially during the summer months. In fact, an acknowledged problem is the occurrence of floods in wet years, associated to intense rain episodes and the rapid flow of water that is typical from mountainous watersheds. In the Vez watershed, the flood regulation service would be best delivered under eucalyptus/pine forestation scenario. Eucalypt and pine species are associated to a reduction in peak flows, mainly due to their rapid growth rates and the ability of their canopy to intercept rainfall during the rainy season (Robinson et al., 2003). The potential for flood regulation in the low mountain sub-basin would be particularly increased under the eucalyptus/pine scenario (Figure 5.5), suggesting this scenario to be favoured if the options for management would focus on the regulation of peak flows. On the other hand, under the same scenario, the provision of water quantity in the low mountain would decrease, which should be considered in a context of climate change in the Vez watershed (Chapter 4).

Soil erosion appears to be best provided under the eucalyptus/pine scenario and the shrubland scenarios (Figure 5.5). In general terms, erosion rates appear to be related to the role played by vegetation in protecting the soil surface (Nunes et al., 2011). However, eucalypt and pines stands should not be intensively managed, otherwise the effect on soil erosion control would be the opposite (Figueiredo et al., 2011). This service was predicted to be less important under oak forestation scenario, as deciduous trees do not protect the soil as effectively during the rainy, cold season (Figure 5.5). It should be noted, however, that SWAT does not consider the structure of understory vegetation, which is usually more complex in native woodlands than in managed planted stands (Nunes et al., 2011). In all cases, fires are an underlying cause of soil erosion and degradation in the Mediterranean region, especially in Portugal where erosion by fires has been a major concern in the last years (Shakesby, 2011; García-Ruiz et al., 2013).

Biomass production and carbon storage were predicted as slightly higher under the current shurbland dominated cover (Figure 5.5). However, the type of biomass from forest stands has a higher economic value (e.g. pulp from eucalypt, timber and wood from pines and oaks), which should be regarded as a good asset to improve the landowners' incomes. Usually, the carbon storage service is considered most important in areas with stable vegetation (Chan et al., 2006). Nevertheless, the long-term carbon sequestration potential of forests can be destroyed by fires, an important carbon emissions component, due to be also influenced by climate change (Sommers et al., 2014). In the Vez watershed, fires have been a constant degradation process, as revealed by the extent of low vegetation areas (scrub and heath), impacting not only the resilience of the biotic communities, but also the carbon storage and the overall provision of ecosystem services (Proença et al., 2010a).

A flow of ecosystem services provision can be observed in Vez watershed, especially in the case of hydrological services, since the high and low mountain are the sub-basins where these ecosystem services are best delivered, whereas most of the corresponding benefits are actually felt downstream in the valley. This is in line with the traditional ecosystem services provision knowledge, in which the provision of services can be considered directional, e.g. the regulation of water by forests in the upstream mountains in a watershed resulting in a benefit downstream (Fisher et al., 2009).

5.4.2. Trade-offs with biodiversity conservation and implications for land management

Oak forestation would be the most favourable scenario for biodiversity conservation value, whereas eucalyptus/pine was the least favourable (Figure 5.4). Eucalypt is an exotic tree species widely planted in Portugal for pulp production, and usually associated to low levels of biodiversity in their stands when compared to native stands (Kardell et al., 1986). Plant and bird diversity in the Vez watershed region is highest in oak forests, followed by pine stands and far less in eucalypt plantations (Proença et al., 2010b). This is particularly important inside protected areas, where eucalypt stands, even if contributing to ecosystem services provision, have negative effects on biodiversity, as emphasised in a recent study in Spain (Onaindia et al., 2013). Forest certification requiring the management for biodiversity conservation objectives is also an important action to promote native forests (Thompson et al., 2011).

In our hypothetical eucalyptus/pine forestation scenario for the whole watershed, a large proportion of eucalypts and pines would be located inside protected areas. Here, the level of naturalness should be maintained, investing in measures for natural regeneration of oak and avoiding ecosystem degradation related with fires and invasive species (Proença et al., 2010b).

Based on the patterns, flows and dynamics of ecosystem services as well as their trade-offs with biodiversity conservation, some recommendations may be suggested regarding the effects of different land cover scenarios on the ecosystem services provision in the Vez watershed. Considering flood regulation was identified as a key challenge, which can be aggravated in the context of climate change, the eucalyptus/pine scenario would appear to be the best option for future management strategies. However, there are three major disadvantages that should be considered: (1) the trade-offs with other services, namely water timing (considered here as the maintenance of summer low flows), which is better provided under the oak and shrubland scenarios; (2) the fire proneness of eucalypt and pine forests (Fernandes, 2012), especially during summer, and the consequences for soil erosion and landscape degradation; and (3) the trade-offs with biodiversity conservation, mainly inside protected areas but also across the watershed. For the latter, conservation strategies considering incentives for the use of native species, especially inside protected areas, would be a good option to promote biodiversity and ecosystem services (Proença et al., 2010b; Onaindia et al., 2013).

Fire smart-management with intervention on vegetation reducing the flammability and increasing resilience (e.g. using native species) in relation to the fire regime can be pointed as efficient strategies (Fernandes, 2012). For the trade-offs with provision of other ecosystem services, spatial optimization simulations could be developed in which eucalypts and pines can be assigned to areas where flood risk mitigation is strategically more effective, provided that forest management regimes are adequate to promote regulation services. Other types of forests could be assigned to other areas in order to improve other ecosystem services, for instance oaks in protected mountain areas for water timing (also positive for biodiversity conservation). The creation of mosaics of native trees well connected through corridors will improve the resilience and connectivity at a landscape scale (Brockerhoff et al., 2013). This would also contribute to maintain and promote landscape diversity across the watershed, which is known for sustain social-ecological resilience and adaptive capacity in a changing world (Chapin et al., 2010).

5.4.3. SWAT as an effective tool for mapping ecosystem services

The inclusion of additional ecosystem services in our framework, using SWAT, is an added value for understanding the processes and services provision using a daily-runoff model. Similar efforts have been done before (Logsdon & Chaubey, 2013), but to our knowledge this is the first time a special emphasis is placed on ecosystem service dynamics under different forestation scenarios, while also considering the biodiversity conservation value. Based on our results and others from previous studies, we advocate that, when accurately calibrated, SWAT can be an important tool for modelling and mapping ecosystem services related to the biophysical processes at the watershed scale. Although it is known as a tool without a central focus on ecosystem services modelling due to a primary module on the hydrological processes and the absence of the demand side of ecosystem service modelling (Vigerstol & Aukema, 2011; Bagstad et al., 2013), it can be used effectively for the biophysical modelling of all hydrological services, and as a complementary tool in more comprehensive modelling approaches.

Future land use/cover policies should consider a holistic perspective as the one presented here, considering not only the hydrological/ecological processes with their related implications for ecosystem services provision, but also considering the spatial conflicts with biodiversity conservation value. In this regard, a current limitation of SWAT is the single consideration of a bundle of ecosystem services, namely those related to watershed processes (hydrological services, biomass production, and carbon storage). Nonetheless, SWAT has proved to be an important tool for modelling and mapping the potential provision of ecosystem services at the watershed scale, thereby contributing to analyse and diversify options for land management and watershed governance.

5.5. Conclusions

SWAT was used to model and map hydrological services and biomass with derived carbon storage at the HRU level, under three land cover scenarios (shrub, oak and eucalyptus/pine). In addition, biodiversity conservation value was mapped to assess the spatial trade-offs between ecosystem services provision. In Vez watershed, the current delivery of ecosystem services is major in the high and low mountain, with less performance in the valley. The high mountain sub-basin is strong in providing water quantity, biomass production and consequent carbon storage. The low mountain is prone to deliver soil erosion control and flood mitigation. When considering the two different forestation scenarios, water quantity decreases considerably in eucalyptus/pine scenario, as well with for water quantity service. Remarkably flood mitigation and soil erosion is improved with eucalyptus/pine scenario in particular in low mountain region. The eucalyptus/pine scenario is the one with more spatial trade-offs with biodiversity value, especially inside protected areas. It seems that different strategies may be suggested for an effective land use planning in Vez watershed. Considering that water quantity is not a problem is Vez watershed and eucalyptus/pine is the scenario with better results for flood regulation, cautions should be taken regarding strategies of conservation (preferably the use of native oak), and fire risk increase.

SWAT has been proved to be an important tool for modelling and mapping ecosystem services generated at the watershed scale, thereby contributing to improve the options for land management.

Acknowledgments

This study was financially supported by FCT (Portuguese Science Foundation) and the European Social Fund through PhD grants: SFRH/BD/66260/2009 (C. Carvalho-Santos) and SFRH/BD/90112/2012 (J. Gonçalves). R. Sousa-Silva was supported by a PhD grant in the framework of the FORBIO Climate project, financed by BRAIN.be, Belgian Research Action through Interdisciplinary research. J. Honrado received support from FCT through project grant PTDC/AAG-MAA/4539/2012 (IND_CHANGE).

Chapter 6

General Discussion and Conclusions

Vez river

6.1. General Discussion

This thesis presents and tests a framework to analyse hydrological services and the role of forests, using a combination of principles and methods of eco-hydrology with concepts and methods from the novel ecosystem services science. The framework encompasses the conceptual foundations from both fields and provides guidelines for evaluating and monitoring hydrological services provision. This chapter discusses the cross-cut topics of the thesis, namely: the newly proposed conceptualization of forest hydrological services; the use of remote sensing to improve the assessment of hydrological services; the assessment of hydrological services based on the application of eco-hydrological modelling frameworks; the development of model-based simulations of hydrological services provision under climate and land use change scenarios; and the adaptive management of hydrological services provision in small watersheds.

6.1.1. Forest hydrological services in a social-ecological framework

In the ecosystem services (ES) literature, conceptualizations have been evolving towards organizing and consolidating the inherent complexity of ecosystem services provision and the downstream societal benefits. Examples of this are the proposals by de Groot (1992), Daily (1997), Elmqvist et al. (2009), MA (2003), Haines-Young and Potschin (2012), Wallace (2007) and de Groot et al. (2010a). Attempts to further organize specific levels inside the broad concept of ecosystem services have emerged, for instance, addressing the valuation and the decision making context of ecosystem services (Fisher et al., 2009), the economic valuation (Boyd & Banzhaf, 2007), discussing the spatial scales of analysis and stakeholders (Hein et al., 2006), addressing land management and the provision of ecosystem services (van Oudenhoven et al., 2012), including the more societal components of the the ES cascade model (Spangenberg et al., 2010), different dimensions of value (Jax et al., 2010), poverty alleviation (Fisher et al., 2013), or their importance in environmental impact assessment (EIA) (Honrado et al., 2013).

Specifically for this thesis, there were three conceptualizations that served as a basis to develop the conceptual framework (presented in chapter 2): i) the conceptualization of the hydrological services by Brauman et al. (2007), ii) the ES cascade model presented in Haines-Young & Potschin (2010) and further disseminated in the TEEB study (de Groot et al., 2010b); and iii) the DPSIR (Drivers, Pressures, State, Impacts and Responses) model adapted to the ecosystem services concept by Rounsevell et al. (2010). The objective was to create an integrative framework that could be useful to understand the biophysical processes and the functions behind the relations between water and the components of landscapes, with an emphasis for forests, in a concise way and considering it in a social-ecological systems context. The motivation was the high importance of promoting forest management as a strategy for the improvement of ecosystem services delivery, associated to the fact that not always the complex relations between forests and water are adequately considered and acknowledged (Crossman et al., 2013). The ultimate goal is to create frameworks addressing specifically a given ecosystem and its related services provision, for instance urban forest services (Dobbs et al., 2011), and now for forest hydrological services (chapter 2). This emphasis on the conceptualization and the identification of reliable and cost-effective indicators also reflected in the subsequent chapters of this thesis, when the review of relevant satellite products was presented (chapter 3), and when the SWAT model was applied to the Vez watershed, considering not only the biophysical processes, but also the drivers and pressures, including scenarios of land use/cover change and future climate conditions (chapter 4).

The ecosystem services concept has been proposed as a promising framework for natural resources management, with complementary benefits and/or consequences for the forest sector (Patterson & Coelho, 2009). These benefits are manifold, from timber and pulp production, carbon sequestration, reduction of soil erosion and flood mitigation, to cultural services (Shvidenko et al., 2005). But the consequences of forestation should also be recognized, such as the reduction in local/regional water yield (Wang et al., 2011). In addition, when plantation forests are implemented, an increase of soil erosion may occur (Figueiredo et al., 2011) as well as changes in fire regime (Fernandes, 2012). Furthermore, when the plantation is done with exotic tree species, a reduction of the local biodiversity may be associated, e.g. in eucalypt stands (Onaindia et al., 2013). However, in other cases plantation forests, mostly in the tropics, are acknowledged for their direct benefits for biodiversity conservation, because they reduce the negative impacts on natural forests by offsetting the need to extract resources (Pawson et al., 2013). In chapter 5, two scenarios of forest occupation were used for a spatiotemporal analysis of service provision. It was not explicitly considered whether those scenarios would be plantation or natural regeneration with their respective consequences, because the aim was only to compare the hydrological consequences of different land cover scenarios. However, eucalypt and pine stands are managed for fast growing, production objectives, oriented towards economic revenues, which is often associated to intensive management. In this case, the provision of hydrological services might be changed due to changes in the structure of stands as well as of the plant undergrowth (Bredemeier, 2011).

6.1.2. Using remote sensing to improve the assessment of hydrological services

Remote sensing observations, especially satellite-based products, offer reliable, relatively low-cost, spatially explicit and near-real time data (de Jong et al., 2004). Those characteristics offer several advantages to the use of satellite-derived products in ecosystem services assessments, regarding the quantification of the provision capacity, as well as their drivers and pressures (Carvalho-Santos et al., 2013). Although the evaluation of the societal demand for services provision has limitations regarding the use of satellite derived products, some proxy indicators using the location of the beneficiaries with high resolution images can be a useful approach (Ayanu et al., 2012).

Likewise, the use of satellite observations is valuable to support the assessment of hydrological services, and the water functions from the ecosystems in general (Pietroniro & Prowse, 2002; van Dijk & Renzullo, 2011; Ayanu et al., 2012; Fernández-Prieto et al., 2012; Su et al., 2012). In this context, it is important to be aware of the available satellite products, as well as of their characteristics in order to apply them adequately in the water management. In chapter 3, a review of several satellite products to evaluate hydrological services provision was presented. The survey revealed how the assessment of water supply and water damage mitigation services can strongly benefit from the use of satellite-based products, contributing to improve the understanding of the processes and functions behind their provision, on a spatially explicit and near-real time basis. Some examples are: the MODIS products for evapotranspiration and for vegetation indices, among other products; the Advanced Microwave Scanning Radiometer (AMSR-e) products for precipitation and soil moisture; and the Water quality bands from MERIS. They were considered among the most promising types of remote sensing products to support the assessment and efficient management of hydrological services, in the optical field (Kumar & Reshmidevi, 2013). In the microwave field, Advanced Synthetic Aperture Radar (ASAR) for soil moisture, and Gravity Recovery and Climate Experiment (GRACE) for groundwater levels, can also be pointed out as useful products for hydrological services monitoring. Ultimately, Sentinel-1 from the European Space Agency (launched on April 2014) is already providing useful information (from C-band SAR data) for long-term monitoring the planet’s land, water and atmosphere (Butler, 2014).

6.1.3. Analysing hydrological services with eco-hydrological modelling tools

Daily-runoff models, such as SWAT, have been identified as proper tools for hydrological services modelling (Crossman et al., 2013). However, they are not entirely recognized as ecosystem services modelling tools, since they do not evaluate other ecosystem services, e.g. cultural services, nor they consider the demand side for services evaluation (Bagstad et al., 2013). Therefore, the gain in accuracy when using hydrological modelling tools should be complemented with other tools for an effective ecosystem services evaluation (Vigerstol & Aukema, 2011). For instance, in the case of a focus on the valuation of hydrological services, SWAT outputs should be complemented with indicators of demography and socio-economy. Although this was not the aim of this thesis, efforts should be done in the future to improve SWAT model for a complete ecosystem services evaluation. A small contribution was done in chapter 5, where a biodiversity valuation exercise was done in parallel with SWAT modelling, suggesting that SWAT can be effectively applied in a broader ecosystem services assessment.

As referred before, demand is a component that traditional hydrological modelling tools do not consider (Vigerstol & Aukema, 2011). Instead, InVEST and other models that consider the demand side can elaborate a more integrative picture of the state of ecosystem services (Nelson et al., 2009). As stressed in chapter 3, demand for services is also difficult to monitor from satellite products, with the location of human settlements and activities being used as a surrogate indicator of demand (Ayanu et al., 2012). In our first modelling exercise (chapter 2) the water supply and erosion control services were evaluated including the demand side. A broader perspective was taken, but at the cost of the accuracy of the hydrological modelling exercise. With SWAT (see chapters 4 and 5), the inclusion of demand is structurally impossible, but some parallel exercises seem to have good results, e.g. the application of indices according to service provision (Logsdon & Chaubey, 2013).

An accurate modelling exercise is a decisive step to have good results in order to support options and strategies for the decision-making process. In strategies to promote forest hydrological services, this can be translated in payments for ecosystem services (PES), e.g. for improving the revenues of hydrological power production (Guo et al., 2000; Nguyen et al., 2013), or for water quality and quantity (Quintero et al., 2009). There are currently over 50 operational PES schemes worldwide, applied mainly in tropical countries and in particular for water quality and sediment reduction (brouwer et al., 2011). However, the monitoring of their performance (e.g. keeping forests for improving water quality) is often not done. Therefore, is not guaranteed that the payment is meeting the primary objective (Kinzig et al., 2011). The only objective that is successfully fulfilled is poverty alleviation, which is an important benefit from PES (Fisher et al., 2013). The conceptualization presented in chapter 2 could be used as support for the creation of new PES and/or to improve the monitoring of the performance of the existing PES. In addition, the suggested indicators and satellite products can be adapted to assess and monitor PES schemes (chapter 3). Whenever possible, hydrological models should be applied to all watersheds subject of PES schemes. However, data gaps associated to the lack of knowledge could jeopardize this application. To overcome data limitations, satellite surrogate indicators could be used to monitor the water functioning of the watershed (Carvalho-Santos et al., 2013) For enabling the teams in the use of hydrological models, training programs should be offered, namely in SWAT or in other, simpler models, for instance WEPP (Water Erosion Prediction Project) from the United Nations.

Global change, namely regarding future climate conditions and land use/cover change, will impact the supply of ecosystem services, which are vital for human well-being (Schroter, 2005). The use of robust and calibrated models, in the case of this thesis SWAT hydrological model, is a good step to further apply scenario analysis. There are many examples in the hydrology scientific literature with the application of SWAT for water resources studies. From the SWAT database (SWAT 2014), 1702 studies have been published since 1984 using SWAT. From these, 81 analysed land use effects, 177 the climate effects, and 22 combined both effects (SWAT, 2014). Examples in the literature of SWAT applied specifically to the assessment of ecosystem services are more limited, e.g. Quintero et al. (2009), Logsdon and Chaubey (2013), and Kepner at al. (2012). This highlights the innovative nature of our studies (see chapters 3 and 4) while at same time stressing the need for further developments.

6.1.4. Model-based scenario analysis of hydrological services

6.1.4.1. Hydrological services in the Vez watershed

As a central objective of this thesis was to understand the consequences of land cover/use and climate change on hydrological services provision, the demand for these services was not explicitly considered in chapters 4 and 5. However, some general considerations can be made regarding demand for water supply and erosion control. In the Arcos de Valdevez municipality (whose boundaries coincide almost 100% with the Vez watershed), the water availability indicator puts this municipality with a fair ratio, *i.e.* water never failed in annual quantitative terms (see Figure 4.2). This results from the high water surplus associated to the low water abstracted (when compared to the more populated municipalities along the coast). For soil erosion control, Arcos de Valdevez is considered with medium risk (see Figure 4.4.g). This is in line with the findings from chapter 4 and 5 with SWAT simulations. The demand, in this case analysed from the risk of soil deposition in dams (as in chapter 2), was not important in the watershed due the absence of dams.

SWAT simulates an average of 5.3 m^3/s a day of discharge in the river, the equivalent of 457 377 m^3 a day, and 166 942 605 m^3/yr. The estimated use of water for urban purposes is 60 m^3/yr per person (on average), which multiplied by 22 847 inhabitants (Census 2011), then by 20 to consider irrigation (INSAAR, 2011), and finally by 12 months, yields a total of

27 416 400 m^3/yr of water used in Arcos de Valdevez. This means that, on average, the use of water is 16% of the total provision of water. In this case, the Vez watershed exports 84% of water to the regions downstream, which is a valuable service contribution to municipalities located downstream and potentially elsewhere in the region. However, this analysis does not consider the annual seasonal variations (winter/summer), and this should be considered for a detailed analysis. Remarkably, estimated soil erosion is low in the Vez watershed, with annual average of 0.02 t/ha.yr, which is under the limit of tolerable rate of soil erosion for Europe, which is between 0.3 and 1 t/ha.yr (Verheijen et al., 2012). The average for Portugal is 1.2 t/ha.yr (Cerdan et al., 2010).

The hydrological services needing more attention in the Vez watershed are water supply timing and flood mitigation, both related with the regulation of the water flows. Since Vez is a mountainous watershed, the response to flow from an intensive rain episode is rapid, associated to shallow soils with low storage capacity, steep slopes as well as low vegetation cover resulting from frequent wildfires (see Table C.1). Although in recent years large floods in Arcos de Valdevez have been infrequent (see Table C.1 in Appendix), in part due to the construction of the flood management infrastructures, caution should be taken regarding a foreseen increase in precipitation in early winter and spring (as described in chapter 4) and also changes in land cover (e.g. decrease in forest area due to fires). Restoring nature, namely by investing in forestation scenarios using native forests, has proved to improve flood mitigation services (Barbedo et al., 2014).

6.1.4.2 Hydrological services under land cover change scenarios

As described in the literature, SWAT is more sensitive to changes in climate than to land cover, which is understandable taking into account that SWAT is forced with climatic parameters (Morán-Tejeda et al., 2013). Nevertheless, in chapter 4 our simulations showed an equal, if not higher sensitivity of SWAT to land cover. Therefore, SWAT can be used to evaluate land cover scenarios, whenever possible compared with observations from field stations in paired catchments studies (e.g. Caramulo mountain, central Portugal, a similar watershed to Vez). One of the main hypotheses tested in this thesis was that the expansion of forest in a watershed, in this case in the Vez watershed, would reduce the total annual water yield. Simulations with SWAT (see chapter 4) indicated a reduction of 8% with the eucalyptus/pine forestation scenario and of 1% with the oak forestation scenario. This small magnitude of change has been also verified with field measurements in the Caramulo mountain with eucalyptus catchments (Hawtree et al., 2014). This can be interpreted as a consequence of the environmental conditions, namely high rainfall rates, high potential evapotranspiration, and shallow soils for water storage.

In this context, Calder's (2002) statement that the influence of forests on water resources is very site specific is valid and applicable in our study. The role of forests on the water cycle has a rationale and a pattern (see Table 2.1), but the magnitude should be evaluated at each specific watershed. In fact, the water quantity service is the one causing more controversy when related to interactions with forests. When the magnitude of change in the water quantity service is small, forests can be assumed to sponsor all the dimensions of hydrological services provision (Figure 2.1). In this thesis, the influence of forest on moisture creation (ET) was not explored, but it is assumed that the product of evapotranspiration in the Vez watershed will be precipitated somewhere else as rain, which is a positive asset for the water balance and the role of forests at regional scales (van der Ent et al., 2010; Ellison et al., 2012). Therefore, forestation in the Vez watershed can be used as a management strategy without causing any constrain for the production of water, considering the current climate conditions. This may not be completely applicable for future climate conditions, especially regarding the reduction of low flows in summer (see chapter 4).

Throughout this thesis, the idea that forests dramatically reduce the total annual water (water supply quantity) has being losing strength: from chapter 2 (where a state-of-the-art on this subject was presented) until chapter 4 and 5 (where the impacts of forest on water resources were addressed). The magnitude of change for the water yield reduction is what should be emphasised.

The idea that forests dramatically reduce the total annual water (water supply quantity; see review in chapter 2) was not supported, for the Vez watershed, by our SWAT simulations in which the impacts of forest on water resources were addressed. Table 6.1 summarises the results from simulations in chapters 4 and 5, a more quantitative approach and a spatial assessment, respectively. A future occupation of agriculture, especially with vineyards, will imply higher input of nitrates, with consequent deterioration of the water quality, and more soil erosion. However, the use of terraces could ameliorate this effect of soil erosion (García-Ruiz, 2010). The low vegetation scenario, which in general terms describes a landscape dominated by low shrubland as a result of wildfires, yielded good performance for water quantity, but less for flood regulation. This degradation scenario corresponds to what has been observed in the Vez watershed over the last decades. The low vegetation scenario is not favourable for the flood regulation service, as scrub and heath vegetation is less water demanding and has less surface for rain interception, so peak flows are exacerbated (Table 6.1). The consequences of repeated fires for soil erosion and land degradation were not simulated in SWAT. However, these risks are well recognized, changing the soil hydrological system (Stoof et al., 2010), affecting soil erosion (García-Ruiz et al., 2013) and reducing of the overall water quality (Smith et al., 2011).

Table 6. 1 - Performance of land cover change scenarios for provision of hydrological services in the Vez watershed (based on results from chapters 4 and 5).

Ecosystem Service	**Chapter 4 –** **watershed outputs**	**Chapter 5 –** **spatial analysis (HRUs weigted by area)**
Water supply		
Quantity	⇑ Low vegetation and Agri vine/ ⇓ Eucalyptus pine	⇑ Shrubland and Oak/ ⇓ Eucalyptus pine
Timing	⇑ Oak/ ⇓ Eucaptus pine	⇑ Shrubland and Oak/ ⇓ Eucalyptus pine
Quality	⇑ Shrubland/ ⇓ Agri vine	⇑ Shrubland
Water damage mitigation		
Erosion control	⇑ Shrubland and Eucalyptus pine/ ⇓ Agri vine and Low vegetation	⇑ Shrubland and Eucalyptus pine / ⇓ Oak
Flood regulation	⇑ Eucalyptus pine / ⇓ Low vegetation	⇑ Eucalyptus pine/ ⇓ Oak and Shrubland

Two forestation scenarios (oak and eucalyptus/pine) were considered according to their hydrological traits. The oak scenario performed better for water quantity and timing (mainly for the maintenance of summer low flows). The fact that oaks do not have leaves during the dormant period increases water infiltration under this scenario. In turn, the eucalyptus/pine scenario was more favourable for the reduction of soil erosion and for decreasing peak flows (flood regulation), as these are evergreen trees. However, oak stands are usually associated to a denser and a more complex understory cover (especially as these stands are only occasionally managed), which may reduce the risk of soil erosion (Nunes et al., 2011). The shrubland scenario also showed good performance for soil erosion control. However, caution should be taken regarding the fire proneness of shrubland, eucalyptus and pine forests, especially during summer, and the consequences for soil erosion (Stoof et al., 2012). Fire smart-management with intervention on vegetation reducing the flammability and increasing resilience (e.g. using native species) in relation to the fire regime can be pointed as efficient strategies (Fernandes, 2012).

The option for the oak scenario would have the additional advantage of fostering the expansion of a native forest type, usually associated to high levels of biodiversity, when compared to eucalyptus and pine species stands (Proença et al., 2010b). The main disadvantage, comparing to the two fast growing species, is that the first economic revenues in terms of key forest products will only occur after a much longer period (50 years, compared with 10 years for eucalyptus and 20 for pine). Although the option for eucalypts stands carries advantages for soil erosion control and flood regulation, the disadvantage of water quantity reduction, especially in summer low flows in the context of climate change, should not be neglected. Even thought, it should be acknowledged that the magnitudes of differences in our simulations are relatively low, and that in general terms there are no restrictions to eucalyptus water use in regions above 1400 mm of precipitation a year (Dye, 2013). On the other hand, eucalyptus is a fast-growing, exotic tree species, with special regulations hampering its use inside some protected areas (Kardell et al., 1986). Moreover, eucalypt stands are more prone to invasion by non-native plants (Lomba et al., 2011). These issues should be considered, as one third of the whole Vez watershed is under Natura 2000 protection (see Figure 5.2b).

6.1.4.3. Effects of climate and interactions with land cover change

It is broadly recognized that the patterns of the global climate have been changing in the last decades, and they are projected to change further in the future (Kovats & Valentini, 2014). Between 1947 and 2006, an increase in temperature and a decrease in precipitation in spring and autumn was observed in Portugal, with extreme heavy precipitation being more pronounced in autumn (de Lima et al., 2013). For areas with Mediterranean type of climate, a generalized warming, a reduction in precipitation rates and the occurrence of more extreme rain episodes are expected (Feng et al., 2014). Likewise, projections for northern Spain (Galicia region) forecast an increase in temperatures with marked uneven distribution of annual precipitation, meaning more rain in the autumn but drier springs and summers (Álvarez et al., 2011). This is in line with the simulations presented in chapter 4, in which an increase in temperature and a decrease in precipitation were assumed. Although the projected magnitude of reduction in yearly precipitation is not severe in the Vez watershed (-3%), the intra-annual changes draw concerns due to a decrease of precipitation in summer and an increase in the autumn/ winter months.

The most important climatic parameter in SWAT is precipitation, which drives how much water is entering into the system (Neitsch et al., 2011). A change in precipitation pattern will have a response in terms of the hydrological outcomes. Future climate conditions in the Vez watershed, under a medium emission scenario, is expected to decrease the annual flow, with special incidence on drier low flows and on the intensification of major peak flows, associated to an increase in soil erosion and the concentration of nitrates in the river (see chapter 4). As the Vez watershed is located in a transition zone between the Mediterranean and the temperate, more humid climates, changes are not so severe as the ones expected for southern Portugal (Kilsby et al., 2007; Stigter et al., 2012; Nunes et al., 2013). Nonetheless, adaptive management strategies with the potential to address the social–ecological complexity of ecosystem services flows, supported by a holistic approach involving natural and social sciences with communication with stakeholders, may be required (Allan et al., 2013). For this, alternative water resources, such as reclaimed wastewater for irrigation and increase of the water use efficiency in agriculture, public supply and domestic use can be pointed as adaptation strategies to cope with future changes (Stigter et al., 2012).

Taking advantage of the synergies and recognising the trade-offs between future climate and land use/cover is also an effective approach (López-Moreno et al., 2013; Shi et al., 2013; Khoi & Suetsugi, 2014). The hydrological consequences from changing climate conditions may be ameliorated or aggravated under different land cover scenarios (chapter 4). As described before, future climate will reduce the low flows, which will be aggravated with the forestation scenario of eucalyptus/pine. This was also verified in a watershed in Spain, where future climate projections together with reforestation scenario will reduce the annual runoff in about 30%, with consequences for reservoir management (López-Moreno et al., 2013). This should also be considered for future plans on hydropower production in the region, which can be highly threatened in dry years, as was verified in a watershed in Spain (Terrado et al., 2014). The combined effects can offset peak flows during winter for flood mitigation in the presence of forests. This would be the positive asset from a reforested watershed.

Future climate will likely increase soil erosion and nitrate concentration, which could be aggravated with a scenario of agricultural expansion, especially in the case of vineyards. The expansion of vineyards has been simulated in the Sordo watershed (Douro basin), with consequent decrease in groundwater quality (Valle Junior et al., 2014) and increase soil losses (Pacheco et al., 2014). The construction of terraces is indicated as a conservation practice to minimize soil erosion (Junior et al., 2014). Overall, considering the combined effects is thus a promising approach for watershed management. This approach is strengthened in the presence of a broader evaluation perspective using the DPSIR framework (see Figure 2.2), and considering stakeholder participation. An interesting nine-step approach for decision-making was presented in a recent study, which includes future climate conditions and the evaluation of various policies with regard to water resource planning and management (Kim & Chung, 2014).

From a more technical perspective, it should be emphasised that the estimated impacts of climate projections can be very dependent on the approach used to downscale climate model data (dynamic or statistical). The important thing here is not to use the GCMs as direct input for simulations because it is inappropriate (Xu et al., 2007). In fact, the range in projected change between downscaling approaches can be as large as the range between different climate models (Kovats & Valentini, 2014). In chapter 4, only the new RCP 4.5 scenario was used, based on four GCMs with statistical downscaling, bias-corrected with ground measurements. Yet, this approach could be further strengthened if a dynamical downscaling would be used as it was done in a study in South Korea (Kim et al., 2013).

6.1.5. Adaptive management of hydrological services in small watersheds

Watersheds are vulnerable to on-going and forecasted environmental and socio-ecological changes, and the provision of hydrological services is a key policy area in the Anthropocene (Allan et al., 2013). This implies a trans-disciplinary effort for an effective implementation of the Integrated Water Management and the Ecosystem Based approaches, connecting the environment (physical and biological) and the human well-being (Savenije & Van der Zaag, 2008; Cook & Spray, 2012). Concerns over water problems are particularly emphasised under the current IAHS (International Association of Hydrological Sciences) decade (2013-2022) of socio-hydrology, identified as “Panta Rhei – Everything Flows”. This concept implies a focus on hydrological systems as a changing interface between environment and society, improving our capability to make predictions for water resources dynamics to support sustainable societal development in a changing environment (Montanari et al., 2013).

Monitoring changes and resilience in ecosystems and in watersheds is an essential step for adaptive water management (Pahl-Wostl, 2006; Iglesias et al., 2011). Here, the usefulness of satellite-based products to monitor the components of hydrological services should be highlighted, especially for the climate related parameters, in order to trace the patterns of possible change (e.g. climate, land cover) (see chapter 3). In parallel, ground-based measurements linked to water resources should be maintained, with a special alert for the Portuguese water information system (SNIRH), which has been closed since 2010. With these available datasets, it is possible to characterise and map hydrological services supply and demand to improve the efficiency of ecosystem services flow inventory (Bangash et al., 2013). This is particularly important to further prioritise socially and economically sensitive policies, such as PES or other ecosystem services-oriented incentives (e.g. agri- and silvi-environmental subsidies).

Mountains are considered as “water towers” and in Portugal the mountainous watersheds are very important for seasonal water supply (Viviroli et al., 2007). Creating governance mechanisms in the Vez watershed, bringing together ES providers, often located in mountains, and ES beneficiaries would be an exceptional way of testing PES in a small watershed context. This could include promoting ecosystem service provision through forestation actions, with direct payments, or through actions involving people in forest plantations or other initiatives. It is important to get society understanding the ecosystem processes and involved in the ecosystem services chain (García-Nieto et al., 2013). To this end, the results from ecosystem services studies should convey clear messages to resource managers and decision makers (Thompson et al., 2011).

6.2 Conclusions

6.2.1. Overarching conclusions

The main objective of the research presented in this thesis was to develop and test conceptual and analytical frameworks for assessing the hydrological ecosystem services provided by forests, to support options for spatial planning and land management. Four studies were presented, each one comprising a different perspective of analysis: (I) a conceptual framework for hydrological services provided by forests, with a regional assessment for northern Portugal; (II) a review of satellite products, with their respective characteristics, potentially useful for hydrological services assessments; (III) an eco-hydrological modelling exercise applied to the Vez watershed, simulating the consequences of different land covers and future climate conditions on water resources; and (IV) a spatially explicit simulation of the consequences of different forest cover options for ecosystem services provision and biodiversity conservation.

The particular novelty of this work is the integration of ecosystem services science with remote sensing and eco-hydrological tools, with a special focus on ecosystem functioning related to forests and water. The dialog among several fields of knowledge requires an integration of the different perspectives, with well-recognized advantages for the creation of novel outputs and syntheses useful for regional and local spatial planning.

The main contributions from this thesis can be summarised as follows:

- A conceptual framework for hydrological services provided by forests was developed, based on the ecosystem services cascade model, with a discussion of the relations between forests and the water flows and an illustration of the framework for northern Portugal (water supply and water damage mitigation);
- An exhaustive review was provided of the most valuable satellite products as well as a discussion of the many advantages that Earth observation offers for the evaluation, management and monitoring of hydrological services;
- An application of the SWAT model to Vez watershed was developed, with calibration of parameters against observed values as well as values presented in the literature and others from satellite products;
- Several SWAT simulations were made, combining land cover change scenarios with future climate conditions under the new RCP 4.5 scenario, for the eco-hydrology of the Vez watershed (including all the hydrological ecosystem services presented in the conceptual framework);

- A spatially explicit assessment was built upon the outputs of SWAT and considering the trade-offs between ecosystem services and biodiversity value for conservation.

Regarding the analytical component of the research developed for this thesis, the following main conclusions can be highlighted:

- Earth observations, and especially satellite-based products, offer reliable, relative low-cost, spatially explicit and near-real time data for evaluating the water functions, with possible integration of routines for data assimilation processes in hydrological modelling;
- Good agreements were obtained between observed values and data simulated by SWAT in the calibration process. Therefore, SWAT can be applied to watersheds with environmental conditions similar to the Vez watershed.
- The scenario analysis with SWAT revealed that the effects of land cover change are in line of what is suggested in the literature, although the magnitude of change is lower. SWAT is generally more sensitive to changes in climate than in land use/cover. Scenario analysis for hydrological services provision is more effective if combined effects of land cover and future climate are considered.

6.2.2. Additional conclusions from the several studies

The main specific conclusions from each chapter can be summarized as follows, adding to the overarching conclusions presented above:

(I) Conceptual framework for hydrological services provided by forests (chapter 2):

- A combination of indicators related to system properties, functions, services and benefits is an effective way of analysing the provision and demand of hydrological services as a whole;
- The framework illustrated for northern Portugal shows that the delivery of hydrological services and forest distribution are shaped by the different climatic characteristics according to the Atlantic or Mediterranean influences;
- The novel framework and indicators can be adapted to other regions for analysing the condition of forest hydrological services;

(II) Review of satellite products available (chapter 3):

- The assessment of water supply and water damage mitigation services can strongly benefit from satellite-based products, considering the different water reservoirs on Earth;

- Satellite products contribute to improve the understanding of the processes and functions behind the provision of hydrological services, on a spatially-explicit and near-real time basis;
- Also, eco-hydrological modelling tools may benefit from satellite products, namely as input data, in data assimilation processes and/or in support of calibration parameters.

(III) Eco-hydrological modelling exercise applied to the Vez watershed (chapter 4)

- A reduction in the total annual water yield is expected with the eucalyptus/pine forestation scenario, in parallel with an attenuation in the peak flows (compared to the current scenario of shrubland);
- The water timing service is favoured in the oak scenario;
- Soil erosion control and nitrogen concentration are higher in the agriculture scenario, but also favoured in the current shrubland cover and in the eucalyptus/pine scenario;
- Water supply timing, with special incidence on drier low flows and flood mitigation (major peak flows), will be affected by future climate conditions, more pronounced for the period 2041-60 (under the RCP 4.5 climate scenario).
- Future climate will increase soil erosion in the period 2021-40, mainly during winter months;
- Combined effects can offset peak flows during winter in the presence of forests under the eucalyptus/pine forestation scenario;
- Low flows in summer will be reduced with future climate and further aggravated with forestation scenarios;
- Soil erosion and nitrogen concentration in the river will increase under future climate and may be aggravated by a scenario of agricultural expansion.

(IV) Spatially explicit simulation of ecosystem services and biodiversity in the Vez watershed (chapter 5):

- The current provision of ecosystem services is more important in the high and low mountain areas than in the valley;
- The performance for the provision of water quantity and timing is better under the shrubland and oak scenarios when compared to eucalyptus/pine scenario;
- The eucalyptus/pine scenario has higher performance for the provision of flood regulation and erosion control, especially in the low mountain sub-basin, although erosion control is also well performed under the shrubland scenario;
- The oak scenario is the one with fewer trade-offs between forest ecosystem services provision and biodiversity conservation.

6.2.3. Recommendations for future research

The new framework for analysing hydrological services in relation to forests presented in this thesis provides theoretical guidance on how to analyse hydrological services and, in the case of the Vez watershed, on how to interpret the effects of different land cover and future climate conditions in a watershed where water scarcity is not a problem, but where the water timing and the regulation of peak flows bring strong concerns. It would be interesting to apply and compare the same simulations for future land cover and climate conditions in watersheds with more pronounced Mediterranean climate. Also considering climate and taking into account that only the RCP 4.5 scenario of climate change was considered in chapter 4, it would be of interest to simulate the hydrological consequences of other climate change scenarios from the new CMIP5 report, in particular the more extreme RCP 8.5 scenario. Regarding changes in land use/cover, it would be interesting to measure in the field the biophysical characteristics of wattle (*Acacia*) species and/or other exotic invasive species in Portugal, to feed the parameters in SWAT. It is unknown what would be the hydrological responses in a watershed where wattles are gaining high expression, as is the case of Vez watershed, especially under climate change.

Societal demand of hydrological services was only considered explicitly in chapter 2 and at a regional scale, as our research objective was more oriented towards the effects of land cover change on hydrological services provision (i.e. the more functional, provision side of the cascade). However, it would be interesting to compare our simulations against the local and regional demand for hydrological services provided in the Vez watershed, even if reliable data on water uses are often hard to get.

Eco-hydrological modelling needs high spatial and temporal resolution ground-based measurements to have a good performance. It is therefore of extreme importance to foster the monitoring of water related services, especially under future climate conditions, and in particular at the local scales, for effective land planning and management. In Portugal, the hydrological information system (SNIRH) has recently stopped the measurements of both the instant level height of some rivers and the climatic parameters from the more local meteorological stations. This means that even calibrated models, such as the one applied to Vez in this thesis cannot be correctly fed for future simulations, because of the lack of precipitation and other climatic variables.

Finally, regarding the importance of the satellite products for water resources monitoring, future research should encompass: (i) the use of satellite products to feed SWAT models at the local scale; and (ii) the testing of proxy indicators of the water functioning in a watershed, derived from satellite products, which could complement or replace the information that is not recorded by national hydrological measurement systems.

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Appendix A

Additional information on chapter 2

Table A. 1 – RUSLE equation factors (K and C) applied in northern Portugal.

Soil type	K factor	Land use type	C factor
Regosols	0.06	Herbaceous; shrubs; sclerophylous vegetation	0.02
Solonchaks	0.18	Evergreen and mixed forest	0.05
Dystric and Eutric Fluvisols	0.19	Broadleaved forest and permanent crops; artificial areas	0.1
Rankers	0.20	Open forests, clear cuts and young plantations; arable land; heterogeneous agricultural areas	0.3
Dystric and Eutric Cambisols	0.31	Burnt areas; aquatic areas	0.5
Ferric Luvisols, Chromic Luvisols and Humic Cambisols	0.32		
Hortic Luvisols	0.36		
Eutric Fluvisols	0.39		

(based on Pimenta, (1998) and Jones et al, (2011))

Table A. 2 - Tree species and respective environmental characteristics.

Latin name	Common name	Environmental characteristics	Contribution to hydrological benefit	PROF*
Quercus suber	Cork oak	Until 800m altitude 10/15m height Meso-Mediterranean	Evergreen trees Small leaves dark green leaves Extensive canopy	Autochthones species Favoring the water infiltration and the absorption by the roots systems Avoid runoff because of the canopy
Quercus ilex	Holmoak	Until 1600m altitude 27m height Meso-Mediterranean humid		
Quercus pyrenaica	Pyrenean oak	800 to 1600m altitude 25 m height Temperate climatic conditions	Deciduous and sometimes marcescent trees (dead leaves in winter that fall in the spring). Extensive canopy	
Quercus robur	Common oak	Until 1600m altitude 30/40m height Siliceous, deep and fresh soils		
Castanea sativa	Chestnuts	Until 1600m altitude Acid and humid soils	Deciduous trees with long leaves	
Pinus pinaster	Maritime pine	30/40m height Humid conditions Light soils	Evergreen trees In spite of the low leaf area, the infiltration is the same during the year.	Resinous species for soil protection and formation because of their strong potential in adaptation
Pinus sylvestris	Scot pine	25/35m height More than 1300m altitude Light mountain soils		
Pinus nigra	European black pine	40/50m height Poor soils, calcareous soils		
Juniperus communis	Juniper	More than 1000m 15m height Calcareous soils	Good adaptation to stony soils. Erosion prevention	
Betulta pubescens	White birch	800 1600m altitude 10/20m height Very humid, poorly drained soils	Deciduous tree	

* PROF – Plano Regional de Ordenamento Florestal (Regional Forest Plans)

Appendix B

Additional information on chapter 4

Model evaluation statistics equations from Moriasi et al. 2007:

Nash-Sutcliffe Efficiency (NSE):

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right)^2} \right]$$

where Yi^{obs} is the *i*th observation for the constituent being evaluated, Yi^{sim} is the *ith* simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and *n* is the total number of observations.

PBIAS – per cent bias

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right) * (100)}{\sum_{i=1}^{n} \left(Y_i^{obs}\right)} \right]$$

PBIAS is the deviation of data being evaluated, expressed as percentage. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias.

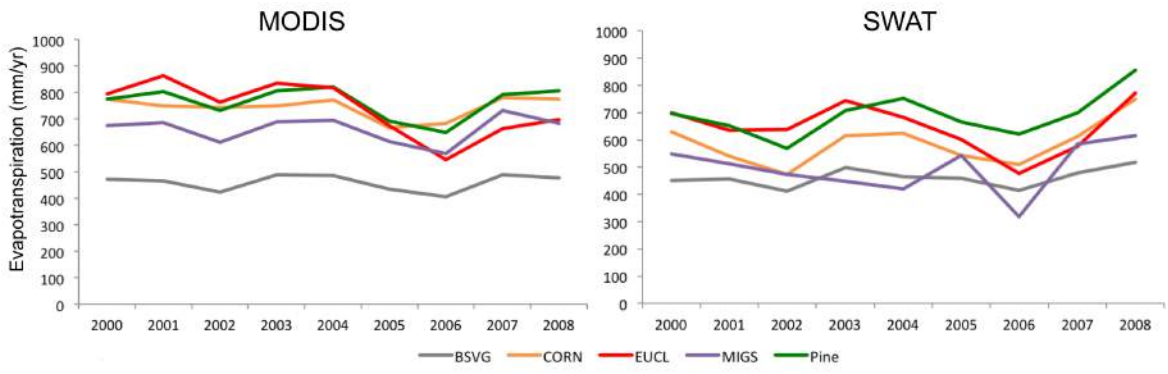


Figure B. 1 - Average evapotranspiration (mm/yr) by different land-covers in Vez basin from MOD16A2 product and simulated by SWAT.

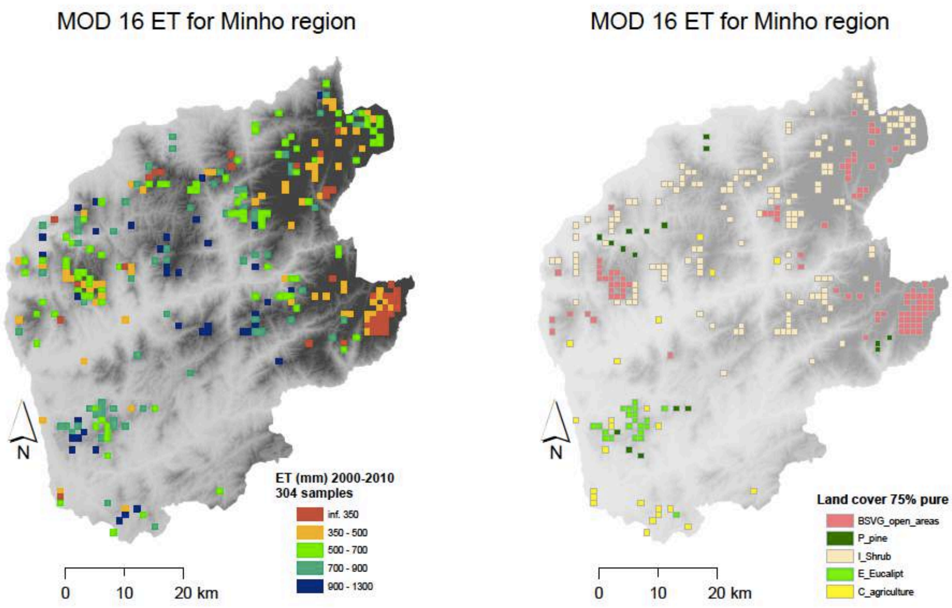


Figure B. 2 – Average evapotranspiration in Minho region, by pure 1km^2 cells (≥ 75% occupied by a single land cover type).

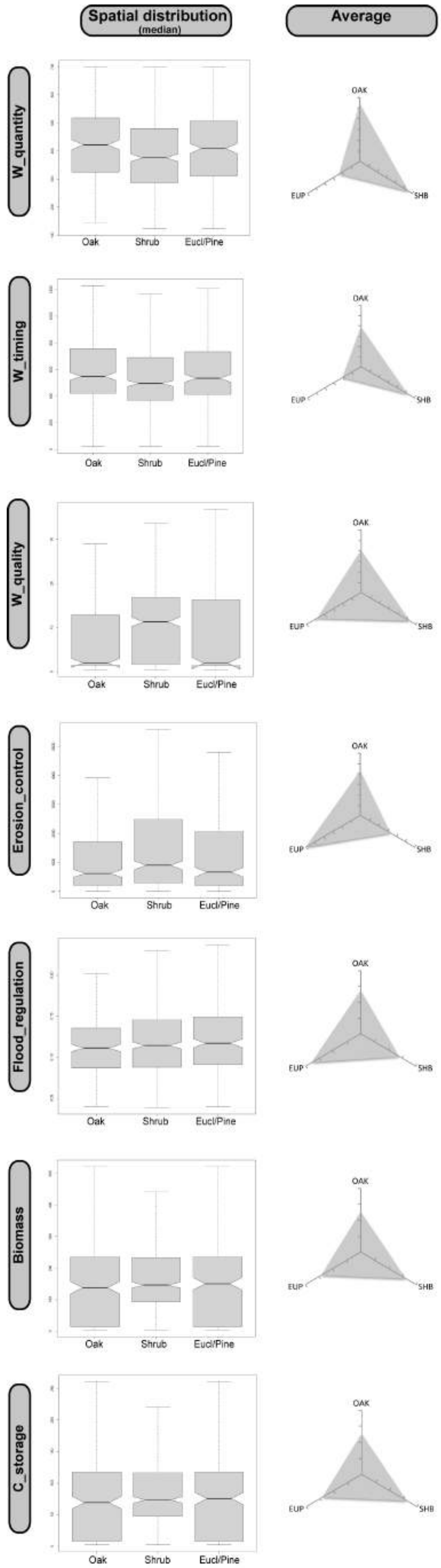
Appendix C

Additional information on chapter 5

Table C. 1 - Biodiversity conservation value of each land cover type for five major taxonomic terrestrial groups. The values were weighted by the protection factor

		Biodiversity conservation value							Factorization			
Land Cover Class	**Area (%)**	**Macrofungi**	**Bryophytes**	**Lichens**	**Flora & Habitats**	**Vertebrates**	**Invertebrates**	**Total**	**No protection (1)**	**Natura 2000 (1.5)**	**PNPG (1.75)**	**Special protection (2)**
Arable land	18.00	5	6	7	15	9	7	**54**	54	81	94.5	108
Fruit trees	0.01	5	5	6	9	9	8	**42**	42	63	73.5	84
Vineyards	0.21	4	7	6	9	7	3	**36**	36	54	63	72
Transitional woodland/shrub	46.71	4	6	8	9	9	10	**46**	46	69	80.5	92
Broad-leaved forest	7.66	15	14	15	14	14	15	**87**	87	130.5	152.25	**174**
Others broad-leaved forest	1.10	13	10	9	14	11	11	**65**	65	97.5	113.75	130
Coniferous forest	7.31	13	8	6	9	10	7	**53**	53	79.5	92.75	106
Eucalyptus forest	0.71	8	4	3	6	6	4	**31**	31	46.5	54.25	62
Shrubs and/or herbaceous vegetation associations	13.72	3	7.5	11	14	10	9	**54.5**	54.5	81.75	95.375	109
Artificial areas	4.33	3	4	3	9	8	3	**30**	30	45	52.5	60
Open spaces with little or no vegetation	0.08	3	3	3	9	8	3	**29**	**29**	43.5	50.75	58
Inland waters	0.14	-	-	-	-	-	-	**-**	-	-	-	-

The macrofungi's valuation took into account the total species richness and the presence of species of high conservation value and/or of social importance. For the bryophytes and lichens, criteria regarding the availability of specific substrates (including rocks, soil, or tree trunks), and some features of these substrates (for instance, the dominant tree species that supports the epiphytic community) were assessed. In addition, the presence of bryophytes and lichens listed in the Directives, Red Lists or known as singular/locally rare/sporadic/endemic, and bryophyte and lichen functional richness understood as the diversity of life forms and life strategies were used as an additional criterion of valuation (Vieira et al., 2012). For the habitats and vascular flora, the valuation was based in different criteria, such as the number of natural habitats, their level of naturalness, threat, singularity and floristic richness, highlighting RELAPE species (acronym for Rare, Endemic, Localised, Threatened with Extinction plants) and habitats listed on Annex I of the EU Habitats Directive. For the insect's valuation, the total species richness, the presence of remarkable species and functional richness were used. Finally, the vertebrate's valuation took into account the level of naturalness, shadow, human disturbance, slope, diversity of tree and shrub species and the presence of aquatic habitats (Honrado & Vieira, 2009).



w_quantity	PVAL	SIGNIF.SYMB
OAK > SRB	8.75936101408966e-06	***
OAK > EUP	0.0555500774775217	.
SRB > OAK	0.999991252774389	
SRB > EUP	0.994459634615293	
EUP > OAK	0.944499699046161	
EUP > SRB	0.00554524020477852	**

w_timing	PVAL	SIGNIF.SYMB
OAK > SRB	0.000779036727849047	***
OAK > EUP	0.218322795186381	
SRB > OAK	0.999221786145505	
SRB > EUP	0.990311683665221	
EUP > OAK	0.781808104954042	
EUP > SRB	0.00969629374322906	**

w_quality	PVAL	SIGNIF.SYMB
OAK > SRB	0.999999985525572	
OAK > EUP	0.846167430916792	
SRB > OAK	1.44999064555706e-08	***
SRB > EUP	0.000226399076263435	***
EUP > OAK	0.153937892591774	
EUP > SRB	0.999773862503782	

erosion_co	PVAL	SIGNIF.SYMB
OAK > SRB	0.999592866934066	
OAK > EUP	0.728552174979564	
SRB > OAK	0.000407585169626429	***
SRB > EUP	0.00485080042198101	**
EUP > OAK	0.271595082785422	
EUP > SRB	0.99515352719733	

flood_reg	PVAL	SIGNIF.SYMB
OAK > SRB	0.933073370678832	
OAK > EUP	0.985759816177426	
SRB > OAK	0.066966532951705	.
SRB > EUP	0.830661665653062	
EUP > OAK	0.0142562748103888	*
EUP > SRB	0.169415990043185	

BIOM	PVAL	SIGNIF.SYMB
OAK > SRB	0.889829806084428	
OAK > EUP	0.821789974250417	
SRB > OAK	0.110228108347594	
SRB > EUP	0.508773326644483	
EUP > OAK	0.178325855269019	
EUP > SRB	0.491349357854933	

c_storage	PVAL	SIGNIF.SYMB
OAK > SRB	0.889829806084428	
OAK > EUP	0.821789974250417	
SRB > OAK	0.110228108347594	
SRB > EUP	0.508773326644483	
EUP > OAK	0.178325855269019	
EUP > SRB	0.491349357854933	

Figure C. 1 – Box plots representing the median value of the distribution in each scenario. (Shrub n = 500; Oak and EUP = 320). The outliers were not considered in the plots. The tables show the Wilcoxon test results, with respective hypothesis ans significance.

Table C. 2 - Water damages in Vez watershed related in the newspaper “Notícias dos Arcos”, from a master thesis (Gonçalves, 2009, FLUP)

Event	Hydrological status in SWAT	Newspaper	Damage
Floods 1987	31 m^3/s (monthly average 3 m^3/s)	1987, 14 October *“Horrible storm scares the region”*	Material damages in houses. 2 days without electricity
Floods 1999	118 m^3/s 22 September	1999, 28 September *“Storm causes incalculable damage”* 1999, 11 November *“Claim for construction of weir”*	1 dead Strong material damages in public water infrastructures, private houses and crop fields (today equivalent half million €)
Mass landslide 2000	Longest period with discharge above 50m^3/s	2000, 7 December *“The tragedy in the municipality”*	4 dead people
Floods 2006	275 m^3/s (23 March) 152 m^3/s (22 October)	2006, 30 March *“Spring came with intense rain”* 2006, 26 October “*Municipality suffers the consequences of bad weather”*	Material damages
Floods 2007	7 m^3/s month for June is high	2007, 21 June “Strong rain in June destroyed pavement in leisure park”	Material damages

Curriculum vitae

Cláudia Carvalho-Santos was born in Malta - Vila do Conde, Portugal, on the 10th of May 1982. In 2000 she started to study Geography at Faculty of Arts, University of Porto, Portugal, with graduation in 2004. She made an internship in the Ministry of Agriculture, Coimbra, Portugal (2006-2007), in the GIS department working with the National Agriculture Reserve. Following a call for research and a strong motivation for nature conservation and sustainable development, Cláudia joined in 2007 a master in Ecology, Environment and Territory at Faculty of Sciences, University of Porto. She visited Alterra Institute, Wageningen, The Netherlands, for nine months in 2009, developing her master thesis on a new methodology for mapping and monitoring High Nature Value farmlands (HNVf) at a local scale.

After her MSc-degree, Cláudia started in 2010 a PhD-study in BIODIV doctoral Program, at the Faculty of Sciences and CIBIO/InBIO, University of Porto, about analyzing hydrological services provision and the role of forests. During the first two years of the PhD (2010-2012), Cláudia was guest PhD student at the Environmental Systems Analysis group, Wageningen University, The Netherlands. She worked on her thesis proposal, attended several courses and developed a scientific paper on the framework to evaluate hydrological services and the role of forests (chapter 2 of this thesis). Back to Porto, Cláudia attended BIODIV classes and pursue with the PhD research. She co-supervised one master student and was made part of the Ind_Change project team (2013-2015). During her PhD, she presented her work in several international conferences: 4th ESP Conference, Wageningen, 2011; TWAM Aveiro, 2013; and 6th ESP Conference, Bali, 2013. In addition, she participated in four summer schools: GISLERS (2010), Alter-net (2010), Gfg2-GNSS (2013); ESA Land Training in Remote Sensing (2014).

Cláudia is actively involved on environmental voluntary work at Quercus-Porto NGO, giving several lectures in schools, developing contents for exhibitions, and field campaigns to clean and monitor a small river. Furthermore, she is also involved in forest plantation actions through a project from CRE Porto.

As both geographer and ecologist, Cláudia is interested in exploring the human relations with the environment and biodiversity for building sustainable options in land management decisions. In particular, she is interested in making Earth Observation products usable for monitoring ecosystem functions and services, especially related to water.

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Educational Programme of SENSE.

Porto, Portugal, 19 September 2014

the Chairman of the SENSE board	the SENSE Director of Education
Prof. dr. Huub Rijnaarts	Dr. Ad van Dommelen

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

KONINKLIJKE NEDERLANDSE
AKADEMIE VAN WETENSCHAPPEN

The SENSE Research School declares that **Ms Cláudia Carvalho dos Santos** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 48.7 ECTS, including the following activities:

SENSE PhD Courses

- Environmental Research in Context (2010)
- Research Context Activity: Active contributions to *Quercus*, the National Association of Nature Conversation in Portugal: preparing exhibition about water and appearance on national television on the subject of 'How to live in a city without cars' (2012-2013)

Other PhD and Advanced MSc Courses

- GISLERS Summer School, Salzburg, Austria (2010)
- 5th ALTER-net Summer School, Peyresq, France (2010)
- Techniques for writing and presenting a scientific paper (2011)
- MSc Course Integrated water management (2011)
- Advanced Course On Global Change And Biodiversity: Implications For Ecosystem Services, Braga, Portugal (2011)
- 2nd Gfg2 Summer School, Potsdam, Germany (2013)

Management and Didactic Skills Training

- Supervision of MSc thesis 'Plant traits and the hydrological services of forest areas in Northern Portugal' (2013)
- Assistant lecturer for Practicals of MSc Course 'Integrated Ecosystem Assessment in Regional Management' (2013)
- Co-organising the 4th ESP International Conference - Ecosystem Services: Integrating Science and Practice, Wageningen, The Netherlands (2011)
- Co-convenor at the special session: 'How to move forward with the ecosystem services concept? – exploring potentials for networking and cooperation', 6th ESP Conference, Bali, Indonesia (2013)

Oral Presentations

- *Hydrological modelling and forestation scenarios - predicting how forests will contribute to the provision of hydrological services in a small watershed using SWAT.* TWAM2013, 16-20 March 2013, Aveiro, Portugal
- *Modelling hydrological services using SWAT – impacts from forestation scenarios in a transitional Mediterranean climatic watershed.* 6th ESP International Conference: making ecosystems services count, 26-30 August 2013, Bali, Indonesia
- Analysing hydrological services provided by forests to support spatial planning and management. CIBIO - Student Seminar, 14 March 2014, Vairão, Portugal

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Dr. ing. Monique Gulickx