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

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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 the 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.



## 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. However, forests are considered the main contributors (Calder, 2002). Forests (soil and vegetation) promote infiltration, increasing soil moisture content and groundwater recharge, contributing to the gradual release of water (Bruijnzeel, 2004). Some benefits can be pointed out, such as supporting hydropower generation and the water supply for households (Brauman et al., 2007; Brown et al., 2005; Farley et al., 2005; Guo et al., 2000). In addition, due to the intervention of tree canopies and the root system, surface runoff is reduced, maintaining soil stability and improving water quality in terms of sediment loading (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 (Bredemeier, 2011; Calder and Aylward, 2006). On the other hand, forests may reduce the annual water yield through increased loss by evapotranspiration,

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consequently limiting the amount of water available in the system (Bosch and Hewlett, 1982; Bredemeier, 2011; Bruijnzeel, 2004; Sahin and Hall, 1996; van Dijk and Keenan, 2007). One important note is that the magnitude of forests influencing hydrological service provision is very site dependent and varies as a function of climate and the biophysical conditions (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 fit in the ecosystem services framework proposed in the context of the TEEB [The Economics of Ecosystems and Biodiversity] project (de Groot et al., 2010b; Haines-Young and Potschin, 2010), and how these components can 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 strongly 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 is presented, which is based on the TEEB ecosystem services framework and on further literature review. Also, a set of indicators to quantify hydrological services is derived from the framework. In addition, an extension of the framework is suggested in the context of social-ecological systems theory. Finally, the framework is 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. Conceptual framework for hydrological services

### 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., 2010b). Accordingly, the TEEB conceptual framework, which is based on the cascade diagram of ecosystem services (Haines-Young and 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., 2010b). 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 and Potschin, 2010). In order to improve the understanding of the provision of hydrological services by forests, a specific framework is 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 are highlighted (Fig. 1).

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 (Fig. 1). Fundamental attributes of ecosystems (properties) provide the mechanisms responsible for generating potential services (de Groot et al., 2010a). 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 (Fig. 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 experience the services, which is only materialized when a beneficiary is present (Haines-Young and 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 (Fig. 1). Note that the relation between

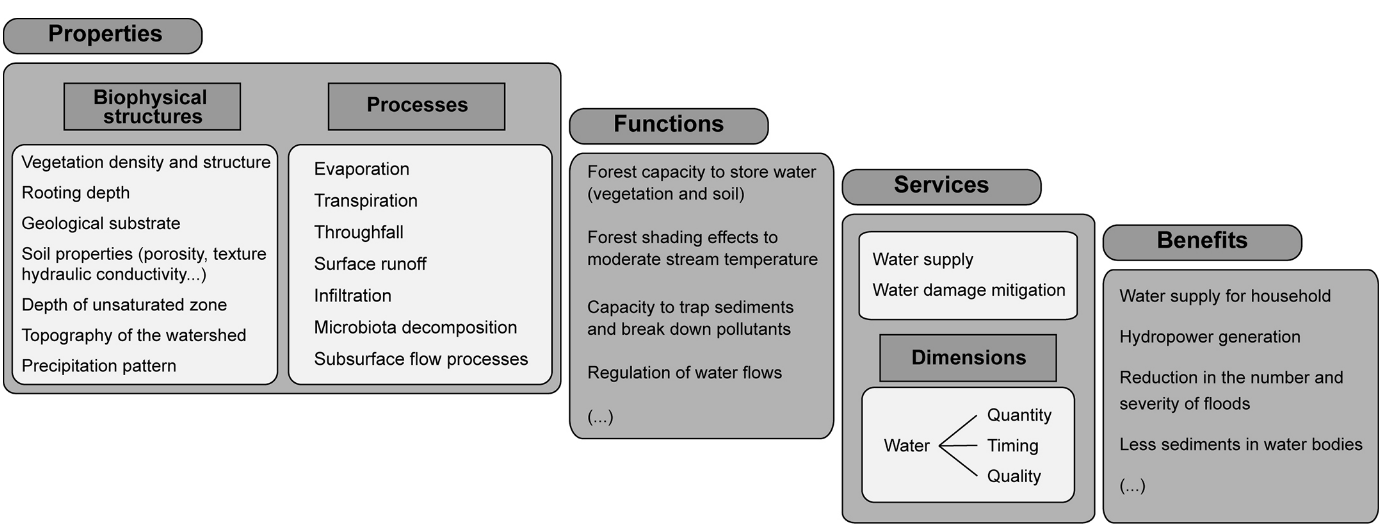


**Fig. 1.** Conceptual framework for hydrological services provision by forests, showing the relationship between the biophysical ecosystem (properties and functions) and the social system (services and benefits). Inside boxes are some examples of each step of the framework.Source: Adapted from the ecosystem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