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Key Points:
- Hydrology-oriented silviculture is proposed to manage semiarid forest with a specific focus on forest-water interactions
- Hydroeconomic models allow to explore integrated water and forest management strategies that maximize total value of water use in the system
- Groundwater recharge may be controlled through forest management

Correspondence to:
A. Garcia-Prats,
agprats@upvnet.upv.es

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A hydroeconomic modeling framework for optimal integrated management of forest and water

Alberto Garcia-Prats[1], Antonio D. del Campo[1], and Manuel Pulido-Velazquez[1]

[1]Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Valencia, Spain

Abstract Forests play a determinant role in the hydrologic cycle, with water being the most important ecosystem service they provide in semiarid regions. However, this contribution is usually neither quantified nor explicitly valued. The aim of this study is to develop a novel hydroeconomic modeling framework for assessing and designing the optimal integrated forest and water management for forested catchments. The optimization model explicitly integrates changes in water yield in the stands (increase in groundwater recharge) induced by forest management and the value of the additional water provided to the system. The model determines the optimal schedule of silvicultural interventions in the stands of the catchment in order to maximize the total net benefit in the system. Canopy cover and biomass evolution over time were simulated using growth and yield allometric equations specific for the species in Mediterranean conditions. Silvicultural operation costs according to stand density and canopy cover were modeled using local cost databases. Groundwater recharge was simulated using HYDRUS, calibrated and validated with data from the experimental plots. In order to illustrate the presented modeling framework, a case study was carried out in a planted pine forest (*Pinus halepensis* Mill.) located in south-western Valencia province (Spain). The optimized scenario increased groundwater recharge. This novel modeling framework can be used in the design of a "payment for environmental services" scheme in which water beneficiaries could contribute to fund and promote efficient forest management operations.

1. Introduction

All around the world, forested catchments supply water for agricultural, urban, industrial, and ecological requirements. In the past, forest and water policies were often based on the assumption that, under any hydrological and ecological circumstance, forest was the best land cover to maximize water yield, groundwater recharge, regulate seasonal flows, and ensure high water quality [*Calder et al.*, 2007; *Hamilton*, 2008]. Unfortunately, the reality is much more complex, and the relationship between forests and water is not so easily solved with such a general rule. The type and density of forest and shrub vegetation, the origin of forest alterations—afforestation, deforestation, forest fires, etc.—or the rainfall regime, are all involved in the hydrological response to vegetation shifts [*Brown et al.*, 2005; *Bargués Tobella et al.*, 2014].

Forest hydrology research conducted during the last 40 years has been summarized in several review papers: *Hibbert* [1967], *Bosch and Hewlett* [1982], *Andréassian* [2004], *Bruijnzeel* [2004], *Brown et al.* [2005], *Calder* [2005, 2007], *van Dijk and Keenan* [2007], or *Levia et al.* [2011]. Research in small experimental paired catchments has clearly shown that forest management can increase annual water yields [*Webb et al.*, 2012; *Van Haveren*, 1988] and groundwater recharge [*Bent*, 2001; *Lasch et al.*, 2005; *Peck and Williamson*, 1987], but have also demonstrated that forest and water interactions are very complex, and have to be analyzed by taking the local conditions into account, especially in semiarid ecosystems.

The scarcity of water for human uses in the Mediterranean may, in some cases, be coupled with impairment between blue (runoff and groundwater recharge) and green (ecosystem evapotranspiration ET) water in dense forests growing on headwater catchments [*Birot and Marc*, 2011]. Vegetation dynamics, which lead to changes in vegetation structure and its water use, may have a major impact on the water cycle, particularly on groundwater recharge because evapotranspiration is a major component of catchment water balances [*Chen et al.*, 2014]. In this context, hydrology-oriented silviculture [*Molina and del Campo*, 2012] is attracting the attention of forest managers, who also need a strategy to either maintain or adapt current forests to precipitation decrease and evapotranspiration increase, due to climate change in the Mediterranean area [*Lindner et al*. 2014; *del Campo et al*., 2014]. Hence, understanding the effects of forest management on vegetation water use and groundwater recharge is particularly important in these regions. One of the main hydrologic features of semiarid regions is the overwhelming importance of groundwater as apposite to streamflow [*Bellot et al*., 2001; *Bellot and Chirino*, 2013], which makes it particularly difficult to establish explicit relationships between blue water and forest management [*Ilstedt et al*., 2016].

Groundwater recharge can be classified into diffuse and localized recharge. Diffuse groundwater recharge, such as recharge related to rainfall percolation throughout the landscape, is strongly influenced by local vegetation and climate characteristics [*Barron et al*., 2012]. On the opposite side is localized recharge, associated with water leakage from surface water features, e.g., rivers or lakes, which are unaffected by vegetation and forest management. Diffuse recharge is responsible for the bulk of groundwater recharge and therefore, we can surmise that an optimal forest cover management exists, one that will produce an additional resource in comparison to other models of forest management, or the absence of management, which makes the problem of forest management unique [*Sandström*, 1998; *Wyatt et al*., 2015; *Ilstedt et al*., 2016]. Diffuse groundwater recharge can be estimated using several direct or indirect methods. Direct measurements are expensive and only representative of a limited area, thus they are largely dependent on the spatial variability. Between the indirect approaches, numerical physically based models are the usual tools in research [e.g., *Chen et al*., 2014; *Dawes et al*., 2012; *Guan et al*., 2010]. These models need to be calibrated and validated using other more easily measurable components of the water cycle, rather than deep percolation, which is obtained as a result of modeling.

Aleppo pine (*Pinus halepensis* Mill.) forests provide landscape quality, soil protection, and hydrological cycle stabilization over approximately 3.5×10^6 ha in the Mediterranean basin [*Fady et al*., 2003; *Zavala et al*., 2000]. It is one of the tree species best adapted to the most arid habitat in the region and it is expected to expand its range when climate change scenarios are taken into consideration. However, most of the Aleppo pine stands originating from reforestation suffer from a lack of management, which is a result of the absence of sufficient economic incentives stemming from conventional forest products. This management vacuum leads to high-density forest stands that can exacerbate rainfall interception losses and contribute to a substantial decrease in groundwater recharge [*Chen et al*., 2014; *van Dijk et al*., 2007] and streamflow [*Calder et al*., 2007; *Hamilton*, 2008; *Gallart and Llorens*, 2003] in forested watersheds. Developing an informed water-oriented management for these forests could boost the multiple benefits they provide and increase their resilience at the same time.

Recent works dealing with adaptive silviculture in Mediterranean semiarid pine forests have addressed the issue of their impact on the water cycle [*Ungar et al*., 2013; *del Campo et al*., 2014; *Garcia-Prats et al*., 2015]. These studies have been very useful in providing a better understanding of the interactions between forests/trees and water and have proven that partial removal of the forest canopy not only produces a decrease in interception and an increase in net rainfall, but also reduces stand transpiration, and increases soil moisture and deep percolation. However, there is a need to move forward from these experimental results, developing guidelines and integrating the well-established knowledge into forest planning schemes that consider both the spatial and temporal dimensions of forest management. By doing this, the transition from timber-oriented to water-oriented silviculture can be realized in those regions where water is by far the most important resource from forested catchments. Thus, a key challenge faced by land, forest, and water planners/managers is that of assimilating previous research findings into integrated water and forest policies, including innovative solutions for balancing the use of the many services provided [*Calder et al*., 2007]. Among these solutions, incentive-based approaches can be found, such as payment for ecosystem services (PES), as a way to induce behavioral changes by compensating individuals or communities for undertaking actions that increase the levels of the ecosystem services desired [*Jacka et al*., 2008].

A holistic approach requires considering the economic dimension of the problem [*Calder*, 2007] and understanding and defining the right economic incentives to achieve the collective management goals. Hydroeconomic modeling may contribute to supporting the analysis and design of economically efficient strategies by integrating the hydrologic, engineering, environmental, and economic aspects of water resources systems within a coherent framework [e.g., *Cai et al*., 2002; *Lund et al*., 2006; *Heinz et al*., 2007; *Harou et al*., 2009; *Pulido-Velazquez et al*., 2008]. Hydroeconomic models (HEMS) represent spatially distributed water resource systems, infrastructure, management options, and economic values in an integrated manner [*Harou et al*., 2009]. Although there is now an extensive literature on the use of hydroeconomic models in river basin management, this has not yet been applied to the integrated management of forest and water. On the basis of a good understanding of how forests interact with the water system, their associated costs, and the benefits from their contribution to the water balance in the basin, HEMs can play a significant role as decision-support tools for efficient forest and water management. By explicitly representing the economic value of water in the system over space and time, HEMs enable the exploration of integrated water and forest management options that maximize the total value of water use in the system.

The objective of this study is to develop a new hydroeconomic modeling framework for assessing and designing the optimal forest and water integrated management of forested catchments. The optimization modeling framework explicitly integrates changes in water yield in the catchment (groundwater recharge changes) induced by forest management, and the value of the additional water provided to the system. This latter component could serve as an indicator for the design of a "payment for environmental services" (PES) scheme in which groundwater beneficiaries could contribute toward funding and promoting efficient forest management operations. An application case study on an Aleppo pine forest is given. This research aims to reveal the potential of integrated water and forest policies and encourage their application by governments and policy makers.

2. Methods

2.1. Silvicultural Operations

Silviculture is based on interventions applied to forests to maintain or enhance their utility for specific purposes such as wood, biomass, biodiversity conservation, or the provision of environmental services [*FAO*, 2015]. Hydrology-oriented silviculture is a particular case that aims to quantify and manipulate the water cycle components in forests according to specific objectives [*Molina and del Campo*, 2012]. Following the definitions in *FAO* [2015], in this work, a silvicultural treatment is a planned program of silvicultural operations that aims to achieve stand-specific objectives by using silvicultural techniques (for example, canopy alterations and thinning) that can be implemented during the entire or partial rotation of a stand.

In semiarid conditions, the productive objectives of forestry are not always viable due to the high costs of exploitation involved: the economic value of conventional forest products is less than that of the required silvicultural operations, which leads to total abandonment. However, this is a near-sighted approach, which fails to take into account the value of water evaporated due to the effect of forest growth and densification arising from the lack of management. In this context, silvicultural operations are more economically efficient when oriented to maximize the economic performance of other services from forests, such as water yield.

2.2. Management Optimization Model

A spatial economic optimization model was developed to define the efficient management of forested catchments in Mediterranean conditions. Management principally involves making periodic decisions on when and where to intervene in the natural evolution of the stands by performing silvicultural operations.

Efficient management maximizes the present value of the net social benefit, defined as the private benefit received from the use of resources (biomass or timber products) plus/minus the external benefits and costs imposed on the society. Since efficient forest management (silviculture) operations will increase water yield (providing additional groundwater recharge), this will provide a positive externality with a value that would correspond to the marginal value (shadow price) of groundwater in the region. The assessment of the marginal value (opportunity cost) of water is often a challenging task. It requires a systems approach and a proper method for characterizing the value of water for the different uses in the system, including the provision of environmental services, in order to develop shadow prices reflecting marginal water values [*Birol et al*., 2006; *Pulido-Velazquez et al*., 2006, 2008].

Since the additional groundwater recharge will benefit the groundwater users, this marginal value could be considered for the design of a PES scheme (in fact, it indicates an upper value for that payment), in which groundwater beneficiaries could help to fund and promote forest management operations. The PES will contribute toward internalizing the positive externality provided by the forest service. With this interpretation, the objective function can be alternatively viewed as the maximization of the net benefit for forest owners, and it will then reproduce their decisions under a PES scheme assuming economic rationality.

The management model of forested catchments under hydrological criteria was formulated as:

$$Max \prod = \sum_s \sum_t \frac{1}{(1+r)^t} \cdot A_s \cdot \left(Y_{s,t} \cdot P_b - MC_{s,t} + DP_{s,t} \cdot MVW \right) \quad (1)$$

where Π is the objective function to be maximized and represents the present value of the net benefit from a forested catchment or management unit (€) defined as biomass or timber production revenues minus management costs (silvicultural operations), including the marginal value of the increased water yield (as additional groundwater recharge). This term is integrated as a social benefit, which could become a real monetary income in the case of incorporating a payment for environmental service. The subindex t in the formulation refers to the year within the planning horizon; r is the annual discount rate; A_s is the area occupied by a homogeneous stand s (ha) into the total management area or catchment; $Y_{s,t}$ is the biomass or timber production of the stand s in year t ($m^3 \cdot ha^{-1}$) if a silvicultural operation took place this year carrying the canopy cover from its current value to 30% (value justified in Appendix A) subject to $Y_{s,t} \geq 0$; P_b is the biomass or timber price ($€ \cdot m^{-3}$); $MC_{s,t}$ includes cost of management (silvicultural operations) of the stand s in year t ($€ \cdot ha^{-1}$) if silvicultural operation took place in this year; $DP_{s,t}$ is the groundwater recharge produced by the stand s in year t depending on the rainfall and the canopy cover ($mm \cdot yr^{-1}$) subject to $DP_{s,t} \geq 0$; and finally MVW is the marginal value of water (groundwater in this case).

The decision variable of the problem is, for each stand s of the catchment or management unit, which year (or years) within the planning horizon a silvicultural intervention is required to maximize the objective function. The decision variable was considered as an integer variable. A typical 100 year planning horizon is used in forest stand rotations. It is worth noting that only extra water produced by means of the silvicultural operation with respect to the nonintervention scenario is included in the objective function.

The application of the optimization management model requires the integration of groundwater recharge, management costs and water values, canopy cover, and biomass/timber yield dynamics along the planning horizon.

Canopy cover and biomass/timber evolution over time were simulated using the growth and yield allometric equations specific for the *Pinus halepensis* in Mediterranean conditions, *Site Quality 14* [*Montero et al*., 2001]. Silvicultural operation costs according to canopy cover were modeled using a polynomial function fitted using cost databases from local forest companies and public administrations. Groundwater recharge was modeled by means of the HYDRUS model, calibrated and validated using experimental data as described hereafter. The modeling framework was applied to the whole forest on which the experimental plots were included. Figure 1 describes the proposed modeling framework. Once the groundwater recharge, canopy cover/biomass dynamics and management cost functions had been obtained from models, the resulting nonlinear optimization problem (NLP) was implemented in MS Excel and solved using the Evolutionary Solver.

2.3. Groundwater Recharge Modeling

Groundwater recharge depends on the precipitation regime and the canopy cover [*Brown et al*., 2005; *Ilstedt et al*., 2016]. In order to relate rainfall, canopy cover, and groundwater recharge into a function to be used in the optimization management model, groundwater recharge has to first be obtained. For this purpose, the HYDRUS-1D model was employed. This model works on a daily basis; daily groundwater recharge was then aggregated on a yearly basis.

2.3.1. HYDRUS-1D

HYDRUS-1D [*Šimunek et al*., 2013] is a software package for simulating the one-dimensional movement of water, heat, and solutes in variably saturated media. The model numerically solves the Richards equation for variably saturated water flow, commonly expressed as:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial x} \left[K(h) \frac{\partial h}{\partial x} + K(h) \right] - S(h) \quad (2)$$

where h is the water potential or pressure head (cm); θ is the volumetric soil water content ($cm^3 \cdot cm^{-3}$); K is the unsaturated hydraulic conductivity ($cm \cdot d^{-1}$); t is the time (days); x is the vertical coordinate (cm); and S

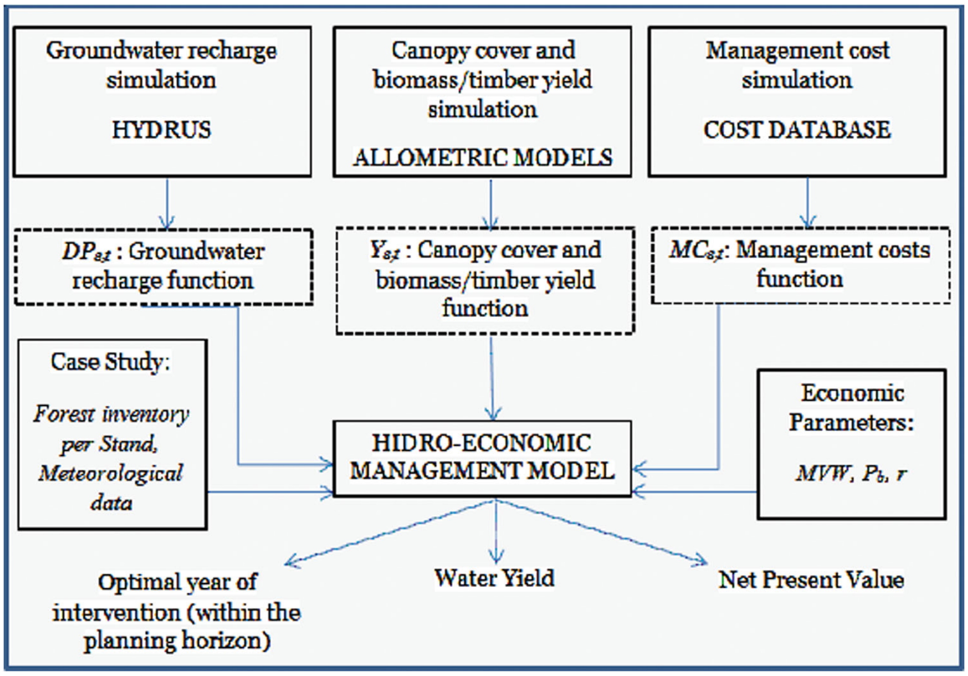

Figure 1. Modeling framework.

is a sink term which represents the volume of water removed per unit time from a unit volume of soil ($cm^3 \cdot cm^{-3} \cdot d^{-1}$), produced by plant water uptake. It should be noted that the units of equations (2–6) are expressed as defined in the HYDRUS, instead of SI's.

The dependence of the hydraulic functions $K(h)$ and $\theta(h)$ on the pressure head can be described using different equations. Here *van Genuchten* [1980] and *Mualem* [1976] equations were used:

$$\theta(h)=\theta_r+\ (\theta_s-\theta_r)[1+(\alpha h)^n]^{-m} \tag{3}$$

$$K(h)=K_s S_e\left[1-\left(1-S_e{}^{1/m}\right)^m\right]^2 \tag{4}$$

where θ_r and θ_s are the residual and saturated water content, respectively ($cm^3 \cdot cm^{-3}$); α (cm^{-1}), n, and m are empirical shape parameters dependent on soil type where $m = 1 - 1/n$; K_s indicates the saturated hydraulic conductivity ($cm \cdot d^{-1}$); l represents the tortuosity/connectivity coefficient; and S_e is the effective water saturation ($0 \leq S_e \leq 1$):

$$S_e=\frac{\theta(h)-\theta_r}{\theta_s-\theta_r} \tag{5}$$

Finally, the sink term (S) can be described as:

$$S(h)=\alpha(h)\cdot S_p \tag{6}$$

where S_p is the potential water uptake rate ($cm\ d^{-1}$) and $\alpha(h)$ is the S-shaped reduction function for water stress, which can be written as follows, according to *van Genuchten and Jury* [1987]:

$$\alpha(h)=\frac{1}{1+\left(\frac{h}{h_{50}}\right)^p} \tag{7}$$

where h_{50} is the pressure head when root water uptake is reduced by 50% and p an experimental constant.

The HYDRUS model solves equations (2–7), making a water balance on a daily basis and providing outcomes on the groundwater recharge [*see Šimunek et al.*, 2013].

2.3.2. HYDRUS Input Data

HYDRUS requires the thickness of the soil layers throughout the soil profile in order to build a geometric finite element model. In this case, two horizons were found: a first 0 horizon of organic matter (litter layer) with a thickness of 5 cm, and an A horizon of mineral soil with a thickness of 50 cm occupied by roots. Under the mineral soil, there are several meters of karstified limestone. Thus, drainage was not limited and the water table was not detected.

Initial hydraulic soil properties were determined using the texture and ROSETTA database [*Schaap et al*., 2001]. Effective hydraulic soil parameters were obtained in the calibration process by inverse modeling.

Atmospheric conditions and free drainage at the bottom of the soil profile were established as boundary conditions. Potential evapotranspiration was obtained in HYDRUS using the Hargreaves formula, and the partitioning into evaporation and transpiration using the Ritchie method. The van Genuchten S-Shaped model was used to take into account root water uptake; their parameters were obtained in the calibration process. Daily rainfall under the canopy (throughfall) was established as time-variable boundary conditions. The first day of simulation soil water content (SWC) was set at the initial condition.

Finally, the daily maximum and minimum temperature, canopy height, albedo, and daily LAI (extrapolated using the monthly curves of *Sprintsin et al*. [2011] from our one-time value of the forest inventory) were defined as meteorological conditions.

2.3.3. HYDRUS Calibration and Validation

The observed values used in the calibration procedure were the transpiration (T) and soil water content at 30 cm depth (SWC) measured in the experimental plots in the period from 1 April 2009 to 1 April 2010, on a daily basis.

The model coefficients selected to accomplish the best fit between the observed and modeled values were the hydraulic soil properties defined in the van Genuchten model (θ_r, θ_s, α, and n) and the root water uptake S-Shaped model of van Genuchten (h_{50} and p). The model parameter estimation procedure was conducted using PEST (a model-independent parameter estimation program) [*Doherty*, 2007]. PEST has implemented a variant of the Gauss-Marquardt-Levenberg method of nonlinear parameter estimation. PEST minimizes the weighted sum of squared residuals between observed and predicted values of T and SWC, respectively. The effective value of soil water content at field capacity ranged from 0.3 to 0.33 $m^3 \cdot m^{-3}$.

In order to validate the model, HYDRUS was applied to a new period using the calibrated values estimated in the calibration process. The validation period was from 2 April 2010 to 31 May 2011, on a daily basis.

A complete assessment of model performance should include at least one absolute error measure and one or several goodness-of-fit measurements [*Legates and McCabe*, 1999]. For these reasons, the behavior of the model was assessed using root-mean-square error (*RMSE*), Index of agreement d [*Willmott*, 1981], Modified Index of agreement d_1 [*Willmott*, 1984], and the Nash-Sutcliffe modeling efficiency E [*Nash and Sutcliffe*, 1970]. Calibration and validation periods were assessed separately. Results can be found in Appendix A.

2.3.4. Groundwater Recharge Function ($DP_{s,t}$)

Groundwater recharge depends on the precipitation regime and the canopy cover [*Brown et al*., 2005; *Ilstedt et al*., 2016]. A polynomial function could be defined in order to relate all these parameters. However, a 2 year period of measured data is enough, as described above, for model calibration and validation, but largely insufficient to relate rainfall, canopy cover and deep percolation into a function to be used in the optimization management model. That is the reason why the groundwater recharge function was derived from HYDRUS modeling using a 25 year period of daily data on precipitation and temperature available at the site (1990–2015) from the meteorological stations nearest to the study site (Ayora-La Hunde, from SAIH-CHJ and INM networks).

Using this HYDRUS-generated 25 year period, groundwater recharge was obtained on a daily basis and aggregated into annual values. The annual groundwater recharge function was fitted as follows:

$$DP_{s,t} = a + b \cdot CC_{s,t} + c \cdot CC_{s,t}{}^2 + d \cdot R_{s,t} + e \cdot R_{s,t}{}^2 + f \cdot CC_{s,t} \cdot R_{s,t} \tag{8}$$

where $DP_{s,t}$ is the groundwater recharge produced by the stand s in year t depending on the rainfall and the canopy cover ($mm \cdot yr^{-1}$); $CC_{s,t}$ is the canopy cover of the stand s in the year t; $R_{s,t}$ is the annual rainfall in the stand s in year t; a, b, c, d, e, and f are the coefficients of the equation obtained by least squares fitting.

Since equation (8) was statistically derived, there could be certain values of rainfall and canopy cover that produces negatives values of $DP_{s,t.}$ In this case, a nonnegativity constraint is applied, and only values $DP_{s,t} \geq 0$ were permitted.

2.4. Canopy Cover and Biomass/Timber Yield Modeling

The measurement of trees and forests is fundamental to the practice of forestry and forest science. Measurements are used to understand how forests grow and develop [*West*, 2009] and are summarized in the forest inventory. Functions that relate plant biomass to one or more other variables that reflect the size of the plant (such as its stem diameter or height) are called allometric relationships [*West*, 2009]. Allometric functions have to be obtained for each species and for each environment, which used to be a typical task carried out by state or regional forest services/forest research centers. In this work, specific measurements for *Pinus halepensis* in Mediterranean environment and allometric equations developed by *Montero et al*. [2001] were employed in order to relate forest inventory data to canopy cover and biomass/timber yield dynamics.

The basal area is related to the age of the stand (*site quality 14*) as follows:

$$BA = 11.72 \cdot ln\,(t) - 25.36 \tag{9}$$

where BA is the basal area ($m^2 \cdot ha^{-1}$) and t is the age of the stand (years). A minimum age constraint has to be applied in order to avoid negative values of BA, in this case $t \geq 9$ years. It is completely logical that a minimum time between interventions was required to produce a certain harvestable timber yield.

On the other hand, canopy cover is related to BA following a logistic growth model:

$$CC_t = \frac{K \cdot CC_0 \cdot e^{r \cdot BA}}{K + CC_0 \cdot (e^{r \cdot BA} - 1)} \tag{10}$$

where CC_t is the canopy cover (%) in year t; CC_0 is the canopy cover at the first year (%, provided by the forest inventory); K is the maximum value of CC (%) or carrying capacity; e is the base of natural logarithms and r is the growth rate ($years^{-1}$). In this work, $K = 100\%$ and $r = 0.12\ year^{-1}$ were employed.

Finally, the volume of biomass or timber yield is related to BA as follows:

$$Y_t = 0.60 \cdot BA^{1.67} \tag{11}$$

where Y_t is the volume of biomass or timber yield ($m^3 \cdot ha^{-1}$) obtained in year t if silvicultural operation took place this year, changing the canopy cover from its current value to 30%.

Dealing with even-aged stands, BA can be obtained using the equation (9) from the age of the stand. When it comes to uneven-aged stands, BA should be obtained by means of a forest inventory, and the CC evolution is BA driven by means of the equation (10).

2.5. Management Cost Function

Silvicultural operations involved in forest management have associated costs that should be accounted for. The more the canopy cover, the greater the volume of biomass and timber yield, but silvicultural operations are consequently more expensive. A polynomial equation relating the cost of silvicultural operations to the reduction of canopy cover involved in the silvicultural operation was fitted to the available data for the case study.

In Spain reference prices of silvicultural operations are published every year by the public company Tragsa, participated by the Spanish government and several regional governments (http://tarifas.tragsa.es). Those prices were employed to build our function.

2.6. Marginal Value of Water (MVW)

The cost of water has two broad components: the cost of its provision and its opportunity cost, or forgone values resulting from water management/allocation decisions [*Pulido-Velazquez et al*., 2013]. Groundwater resources have public good characteristics: people who extract and use them do not pay for the scarcity rents or opportunity costs (both in terms of quality and quantity), but only for the private extraction costs.

When these opportunity costs go unrecognized, the result is an inefficiently high extraction or pollution rate over time and space [*Koundouri*, 2004].

As discussed before, many studies have demonstrated that forest management can increase annual water yields. This added value will benefit the groundwater users, and so, it could be the basis for the design of a PES scheme, in which groundwater beneficiaries could help to fund the forest management operations.

Hence, this extra amount of water produced by forest management has to be included in the management optimization model as an income for the forest industry to be paid by the water-users as payment for environmental services. *Pulido-Velazquez et al*. [2013] presented a framework to determine the *MVW* at the basin scale. This value will depend on the economic value of water for the competing uses, as well as on water scarcity, the operational constraints and infrastructure and storage capacity.

3. Case Study: Materials and Models' Implementation

The study (experimental plots) was carried out in a planted pine forest located in the south-west region of the Valencia province in Spain (39°05′30″N, 1°12′30″W) at 950 m a.s.l. These experimental plots form part of the "La Hunde" public forest. With an average annual rainfall of 465.7 mm and mean annual temperature of 13.7°C, the mean annual potential evapotranspiration is 749 mm (using *Thornthwaite* [1948]) and the reference evapotranspiration, 1200 mm (using *Hargreaves and Samani* [1985]). The soils have a basic pH of 7.6 and are relatively shallow (0.5–0.6 m), with a sandy, silty loam texture. The *P. halepensis* plantations were established in the area during the late 1940s with high densities (approximately 1500 trees ha^{-1}), and no forest management has been carried out since then due to the role of the forest in soil protection. The experimental setup of this work was established using a randomized block design with three blocks of 0.36 ha each. Each block was further divided into three plots (30 $\times$ 30 m), corresponding to thinning treatments performed in 2008 at different intensities (High-T10, Moderate-T30, and Low-T60) and a control plot (T100). The forest inventory of the treatment plots is summarized in Table A1. The silvicultural operation consisted in a thinning treatment. Timber and debris were removed and piled outside the plots.

3.1. Groundwater Recharge Function

The calibrated and validated HYDRUS model (see Appendix A) was applied to a new 25 year period in order to obtain the groundwater recharge function (equation (8)) by least squares fitting. The mean water balance for the simulated 25 year period is presented in Table 1.

The results obtained are in accordance with other studies in semiarid regions, such as *Ilstedt et al*. [2016], which demonstrated that there is a canopy cover that maximizes groundwater recharge. As canopy cover is reduced, the Evaporation-Transpiration binomial remains constant but its relative importance changes. Maximum transpiration occurred when the canopy cover was higher, and minimum transpiration took place when the canopy cover was lower, and vice versa with evaporation. Interception decreases as canopy cover is reduced. The higher amount of precipitation that reaches the soil increased both runoff and groundwater recharge, although this effect disappears when the canopy cover reaches a certain value, established in this study as 30–40% of canopy cover. Empirical results from a research plot on the site demonstrated that groundwater recharge occur mainly in the wet season at the expense of decreased rainfall interception [*del Campo et al*., 2014]. Since runoff is less sensitive (according to our experimental plots) to silvicultural interventions than groundwater recharge, the changes in runoff has not be taken into account in the hydroeconomic model. A future enhancement of the model would be to take runoff into account, which requires to define a runoff function as done for groundwater recharge (see Appendix A)

Table 1. Annual HYDRUS-Modeled Experimental Plots Water Balance

Treatment	Precipitation (mm)	Interception (mm)	Transpiration (mm)	Evaporation (mm)	Groundwater Recharge (mm)	Runoff (mm)
T100	483.30	180.57	139.62	130.80	26.52	5.78
T60	483.30	141.08	116.42	161.78	42.15	21.86
T30	483.30	115.81	103.28	182.76	78.30	29.13
T10	483.30	52.67	77.30	211.70	82.61	33.05

In Mediterranean river basins, as in other semiarid and water scarcity-prone areas, it is possible to differentiate the upper forested catchments with natural flow regimen from the downstream catchment areas with regulated flow regimen, where the water resources generated upstream are usually employed. That is why, in this study, all water that escapes from the root system of the forest is considered to become groundwater recharge. It is evident that a certain amount of this water will reach the aquifer and another amount will get to the base flow of the river, ending up in a reservoir. However, this does not matter because they are two expressions of the same thing: the blue water that will be stored and/or consumed in the lower agricultural and urban areas. The proposed hydroeconomic modeling framework is intended to define the optimal forest management, regardless of who the beneficiaries are.

3.2. Economic Components

For the development of the management cost function, several local forest companies and administrations were consulted for cost-related information. The proposed management cost function is:

$$MC_t = 900 + 28.62 \cdot \Delta CC - 0.029 \cdot \Delta CC^2 - 0.00048 \cdot \Delta CC^3 \quad (12)$$

where MC_t includes the cost of management (silvicultural operations) of the stand in year t (€·ha^{-1}) if silvicultural operation took place that year t, and ΔCC is the reduction of canopy cover involved in the silvicultural operation (%).

Biomass or timber price (P_b) for the *Pinus halepensis* was established at around 25 €·m^{-3} timber (logs piled at a logging park in the forest).

In this work we assume a constant value of the marginal value of water $MVW = 0.175$ (average) €·m^{-3} [*Pulido-Velazquez et al.*, 2013], fixed in the optimization process.

A sensitivity analysis was performed on the effect of increasing or decreasing the values of the economic parameters P_b and MVW.

4. Scenarios and Results

Rotation in forestry is the planned number of years between the stand formation or regeneration and the time when it is felled for the final harvest [*Dikstra and Heinrich*, 1996]. The typical rotation for *Pinus halepensis* in Mediterranean conditions is about 75–100 years. That is the reason why the planning horizon was established on a 100 year period basis.

To apply the optimization management model to a 100 year planning horizon, the same period of daily precipitation was needed. Using the same 25 year series of actual meteorological data utilized with HYDRUS to fit the groundwater recharge function, a new 100 year series was generated using the CLIGEN model. CLIGEN is a stochastic weather generator that produces daily time series estimates of precipitation, temperature, dew point, wind, and solar radiation for a single geographic point, based on average monthly measurements for the period of climatic record, such as means, standard deviations, and skewness [*Nicks and Gander*, 1994; *Flanagan and Nearing*, 1995; *Laflen et al.*, 1991].

Three different scenarios have been considered to illustrate the applicability of the proposed approach. Scenario 0 or nonmanagement scenario, Scenario 1 obtained from the optimization model, and Scenario 2 or sensitivity analysis of the economic parameters that could change the most efficient management strategy (*MVW*, P_b, and *r*).

4.1. Scenario 0

First of all, a scenario 0 of nonintervention (business-as-usual) was defined. In this scenario, no optimization process took place. According to the forest inventory for the case study (Table A1), equations (1) and (8)–(12) were applied to each year of the planning horizon and summed up. This scenario is important in order to know how much groundwater recharge will be produced along the planning horizon without intervention. In this situation, the net benefit is considered as 0 because there were no management costs, no biomass/timber incomes and no additional groundwater recharge (see Table 2).

Table 2. Results of Optimized Management Versus No Management Scenario

Stand	Year First Intervention	Year Second Intervention	Net Benefit (€·ha^{-1}) Scenario 0	Net Benefit (€·ha^{-1}) Scenario 1	Groundwater Recharge (mm) Scenario 0	Groundwater Recharge (mm) Scenario 1	Increment of Number of Years ($DP >$ O mm) (%) Scenarios 0–1
Stand D	8	84	0	109.91	405.33	2347.44	32
Stand C	32	83	0	38.27	771.28	2721.56	32
Stand B	29	79	0	68.76	550.15	2444.20	37
Stand A	12	84	0	118.42	449.82	2360.47	31
Total management area			0	335.4	513.52	2435.45	33

4.2. Scenario 1

In Scenario 1, the optimization model was applied to the management area. The economic parameters of the model were fixed at their current values (P_b as 25 €·m^{-3} and r, 0.05) and a MVW of 0.175 €·m^{-3} was considered (as the mean value of its range). The model defines the economically best years to intervene with a silvicultural operation as the ones that yields the highest net present value. Table 2 shows the groundwater recharge (mm) and net present value were the main results of the model. The discounted net present value was 335.4 €·ha^{-1}. Groundwater recharge obtained by means of the optimized management increased from 514 to 2435 mm, that is to say 1921 mm of additional water in respect of the current state, therefore 19.2 mm yr^{-1} or 192 m^3·ha^{-1} yr^{-1} on average. If we consider the marginal value of water as a price to be paid by the groundwater users (it would actually represent an upper boundary of that price), in this context the forest owner could receive an amount of 28.21 €·ha^{-1} every year, which is calculated as the annual equivalent payment for the whole 100 year period of the income from groundwater recharge at the MVW rate. However, perhaps the most important effect when Scenarios 0 and 1 were compared was the increase in the regularity of groundwater recharge. The number of years with $DP > 0$ mm was on average 33% higher by means of the optimized management than the one obtained in the current situation, which lacks forest management.

The number of interventions recommended in all stands was two, being earlier or later within the planning horizon according to the structure of each stand (Table A1, forest inventory). The more CC and BA, the sooner the recommended intervention. Cumulated groundwater recharge of Scenarios 0 and 1 along the planning horizon can be seen in Figure 2. In this plot, it could be observed that in Scenario 0 there are many consecutive years without groundwater recharge, and only years with a high amount of precipitation obtained small increments of DP. However, in Scenario 1, the effect of the first and second interventions can be seen clearly, as in years 10 and 85, with rapid increments of cumulated groundwater recharge. From year 60 to year 85, a clear stagnation of DP was observed as the stand reaches high values of CC, but any additional intervention would lower the net benefit in this setting. Finally, canopy cover evolution along the planning horizon for scenarios 0 and 1 can be seen in Figure 3.

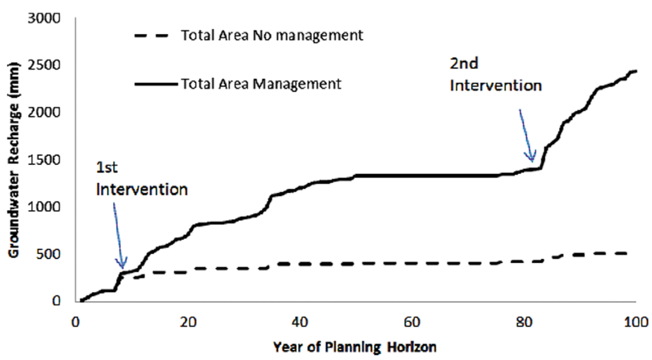

Figure 2. Cumulated groundwater recharge along the planning horizon for scenarios 0 (no management) and 1 (management).

4.3. Scenario 2

In order to know how the economic parameters of the model were affecting the obtained results in the base scenario, a sensitivity analysis was performed. In this scenario, new optimization runs were made changing the value of MVW, P_b, and r; only one parameter was changed while the others were kept constant.

The marginal value of water (MVW) was sequentially increased for new runs of the optimization management model. Results are shown in Table 3.

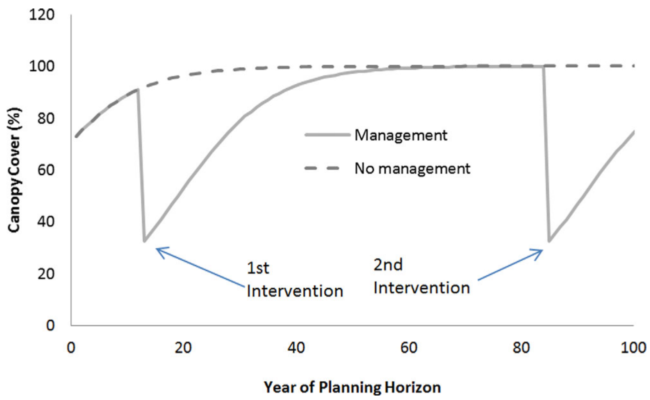

Figure 3. Canopy cover evolution along the planning horizon for scenarios 0 (no management) and 1 (management) for stand A.

The first row shows results corresponding to the situation of no payment for environmental service ($MVW = 0$ €·m^{-3}). By applying the optimization model, it was possible to estimate the maximum net benefit produced by exploiting the biomass/timber obtained in the silvicultural operations without any economic compensation. We can claim that, in the Mediterranean context, forestry profitability has such a low value that it is not appealing to forest owners (near zero €·ha^{-1}·yr^{-1}), and that is probably the reason why forestry operations are being abandoned. Depending on this value, the more *MVW*, the more groundwater recharge, net benefit and interventions were obtained. Net benefit ranged from 95 to 1064 €·ha^{-1} when *MVW* takes values of 0.04 and 0.31, respectively [*Pulido-Velazquez et al.*, 2013]. Groundwater recharge increased significantly from 1337 to 3417 mm for the same interval of *MVW*. As far as the number of recommended interventions was concerned, the results ranged from 1 to 4. Finally, the number of years with a null value of groundwater recharge was also analyzed. The increment of years with DP $>$ 0 mm increased from 16 to 26% when *MVW* takes the value of 0.04 €·m^{-3} to 43–57% when *MVW* takes the value of 0.31 €·m^{-3}.

Biomass or timber price (P_b) was sequentially increased and the optimization of management executed again. Results are shown in Table 4. The first row in Table 4 shows the results corresponding to a situation in which the product obtained in the silvicultural operations has no economic value, and the payment for environmental service ($MVW = 0.175$ €·m^{-3}) would be the only expected income. These results point out that a minimum value of 10 €·m^{-3} for biomass/timber product was needed in order to obtain profitability. For lesser values the model does not recommended any intervention. From this value upward, the more P_b, the more groundwater recharge, net benefit and interventions were obtained. The net benefit ranged from 8.5 to 1738 €·ha^{-1} when P_b takes values of 10 and 50 €·m^{-3}, respectively. Groundwater recharge increased significantly from 1602 to 3302 mm for the same interval of P_b. However, from $P_b = 30$ €·m^{-3} upward, groundwater recharge suffers from a stagnation, and the increments obtained were small. As far as the

Table 3. Sensitivity Analysis for the Marginal Value of Water (MVW)[a]

MVW (€·m^{-3})	Net Benefit (€·ha^{-1})	Total Groundwater Recharge (mm)	Extra Groundwater Recharge[b] (mm)	Number of Interventions[c]	Increment of Number Of Years ($DP >$ O mm) (%)[c]
0.00	59.88	1336.96	823.44	1	26–16
0.04	95.12	1376.64	863.12	1	26–16
0.06	121.17	1579.58	1066.06	1–2	26–16
0.08	145.77	1819.51	1305.99	2	28–16
0.1	169.68	1889.56	1376.04	2	34–16
0.12	196.26	2039.91	1526.39	2	34–18
0.14	240.36	2340.61	1827.09	2	34–27
0.16	282.25	2289.89	1776.37	2	37–27
0.18	354.86	2496.19	1982.67	2	39–32
0.20	423.50	2587.22	2073.70	2–3	48–32
0.22	534.81	2680.45	2166.93	2–3	47–32
0.24	610.51	2675.80	2162.28	2–3	47–32
0.26	721.09	2938.22	2424.70	2–3	51–32
0.28	827.19	3184.85	2671.33	3	51–43
0.30	991.70	3346.79	2833.27	3–4	57–43
0.31	1064.03	3416.98	2903.46	4	57–43

[a]Cumulated results for the entire planning horizon.
[b]After subtracting groundwater recharge in no-management situation (Scenario 0).
[c]Variable according to the Stand.

Table 4. Sensitivity Analysis for Timber Price (P_b)[a]

P_b (€·m^{-3})	Net Benefit (€·ha^{-1})	Total Groundwater Recharge (mm)	Extra Groundwater[c] Recharge (mm)	Number Of Interventions[b]	Increment of Number Of Years ($DP > O$ mm) (%)[b]
0	0	513.52	0.00	0	0
5	0.00	513.52	0.00	0	0
10	8.56	1601.70	1088.18	1	21–13
15	58.68	1754.71	1241.19	2	30–15
20	155.60	2190.92	1677.40	2	36–16
25	335.36	2435.45	1921.93	2	37–29
30	580.33	2821.22	2307.70	2	49–38
35	828.69	2867.76	2354.25	3	54–38
40	1100.92	3033.30	2519.78	3	54–40
45	1431.70	3151.55	2638.03	3	55–44
50	1738.74	3301.92	2788.41	3–4	56–44

[a]Results for the entire planning horizon.
[b]Variable according to the Stand.
[c]After subtracting Groundwater recharge in no-management situation (Scenario 0).

number of recommended interventions was concerned, the results ranged from 1 to 4. Finally, the number of years with a null value of groundwater recharge was also analyzed.

The increment of years with $DP > 0$ mm increased from 0% when P_b takes the value of 0 €·m^{-3} to 44–56% when P_b takes the value of 50 €·m^{-3}.

The last parameter studied in the sensitivity analysis was the annual discount rate (r). As before, r was sequentially increased and the optimization of management executed again. The results are shown in Table 5. The results obtained indicate that groundwater recharge is not significantly sensitive to the value of r except for $r = 0$. In that situation the model recommended one intervention when groundwater recharge was 1520 mm, otherwise it recommended two interventions and groundwater recharge was kept constant at around 2500 mm, regardless of the value of r. However, this is not the case with the present value of the net benefit that follows an exponential decay as r increases. As far as the regularity of groundwater recharge, the number of years with $DP > 0$ mm increased from 11 to 21% when r takes the value of 0 to 33–41% when r takes another value.

5. Discussion and Conclusions

Managing a forest for water saving and production is a powerful tool to increment water resources in water scarcity-prone watersheds. The complex relationships between forests and the hydrological cycle, coupled with the ongoing expansion of woodlands, climatic changes, and the diminishing trend in water flows, require hydrological factors to be consider in forest management. While the hydrological role of forests has traditionally been a mainstay of forest management, water quantification depending on forest cover, structure or density remains a challenge [*Ungar et al.*, 2013; *del Campo et al.*, 2014; *Ilstedt et al.*, 2016]. In this study, a novel hydroeconomic modeling framework for assessing and designing the optimal forest and

Table 5. Sensitivity Analysis for the Annual Discount Rate (r)[a]

R	Net Present Benefit (€·ha^{-1})	Total Groundwater Recharge (mm)	Additional Groundwater[c] Recharge (mm)	Number Of Interventions[b]	Increment of Number Of Years (DP > O mm) (%)[b]
0	3444.32	1520.35	1006.83	1	21–11
0.01	1718.44	2417.41	1903.89	2	34–29
0.02	1073.65	2504.55	1991.03	2	34–28
0.03	678.65	2504.93	1991.41	2	41–31
0.04	458.07	2462.77	1949.25	2	38–33
0.05	335.36	2435.45	1921.93	2	37–29
0.06	251.38	2354.05	1840.53	2	40–27
0.07	200.36	2441.13	1927.61	2	40–33
0.08	152.36	2413.28	1899.76	2	41–36

[a]Results for the entire planning horizon.
[b]Variable according to the Stand.
[c]After subtracting Groundwater recharge in no-management situation (Scenario 0).

water integrated management of forested catchments was developed. The modeling framework explicitly integrates changes in groundwater recharge in the catchment induced by forest management.

The modeling framework presented could be applied to any other forest management unit or forested catchment by replacing the specific functions that represented groundwater recharge, management costs, canopy cover and biomass/timber yield dynamics along the planning horizon, for those specific to the new geographical zone. However, the assumptions considered refers to this specific case study, while they should be at least preliminary assessed case to case, and possibly neglected if not relevant or not sensitive.

In order to illustrate the applicability of the proposed methodology, a case study was developed. In any case, the obtained results must not be understood as general results but rather as particular results for the area of study. Nevertheless as the results of the case study application have shown, efficient forest management can produce an important increase in groundwater recharge, which could provide substantial benefits to groundwater users and forest owners, clearly surpassing the operating costs (under the assumed marginal value of water). The value of this increased recharge will be higher under water scarcity conditions and with high-value uses.

This modeling framework can be used in the design of a "payment for environmental services" scheme in which water beneficiaries could contribute to fund and promote efficient forest management operations. However, in applying the proposed model we have solved only the first step: the design of efficient policy mechanisms to modify forest-owner decisions toward hydrology-oriented silviculture choices, instead of the current timber-oriented silviculture that leads to forest abandonment, with the demonstrated impact on water yield in Mediterranean conditions. The second step needs to answer the question "*qui prodest?*," i.e., who are the real beneficiaries? This second step has to be answered by taking into account the hydrologic functioning of the whole basin, the aquifers, the reservoirs, stream-aquifer interacion, etc. Once the increment in groundwater recharge due to forest management has been established, identifying the final users of these new water resources is the challenging task for a fair PES scheme. A detailed economic characterization of the economic value of water for the different water uses would also allowed a more accurate representation of the economic implications of the forest management actions. It would enable the analysis of the temporal variation of the marginal water values with changes in water availability and in the demand for water (the marginal value of water will be higher during water scarcity periods). Finally, climate and land use changes will certainly have implications on both the forest and the water (hydrological) cycle and, despite the additional uncertainties, it needs to be further investigated in an extension of this analysis for the study area.

Appendix A1. Study Site and Experimental Determinations for HYDRUS Calibration and Validation

The experimental setup of this work was the same as that described by *del Campo et al.* [2014] and *Garcia-Prats et al.* [2015], where an experimental area planted with Aleppo pine was established using a randomized block design with three blocks, 0.36 ha each. Each block was further divided into three plots (30 $\times$ 30 m), corresponding to thinning treatments performed in 2008 at different intensities (High-T10, Moderate-T30, and Low-T60) and a control plot (T100). The forest inventory of the treatment plots is

Table A1. Experimental Plots and Case Study Forest Inventory[a]

Experimental Plot Treatment	CC (%)	Area (ha)	Density (trees·ha^{-1})	DBH (cm)	Height (m)	BA (m^2·ha^{-1})
T100 (control)	84	0.36	1,489	17.8	11.5	40.1
T60 (low intensity)	68	0.36	744	21.2	12.2	27.2
T30 (moderate intensity)	50	0.36	478	17.5	11.3	18.2
T10 (high intensity)	22	0.36	178	20.4	12.2	9.4
Case Study Stands						
A	73.0	941	468	18.4	9.6	14.0
B	64.7	766	484	17.1	8.4	11.0
C	50.7	496	307	15.5	6.2	6.3
D	76.8	887	708	17.1	8.8	17.3

[a]CC = Canopy Cover, DBH = Diameter at breast height, BA = basal area. After *Molina and del Campo* [2012], *del Campo et al.* [2014], and *Calabuig-Vila* [2012].

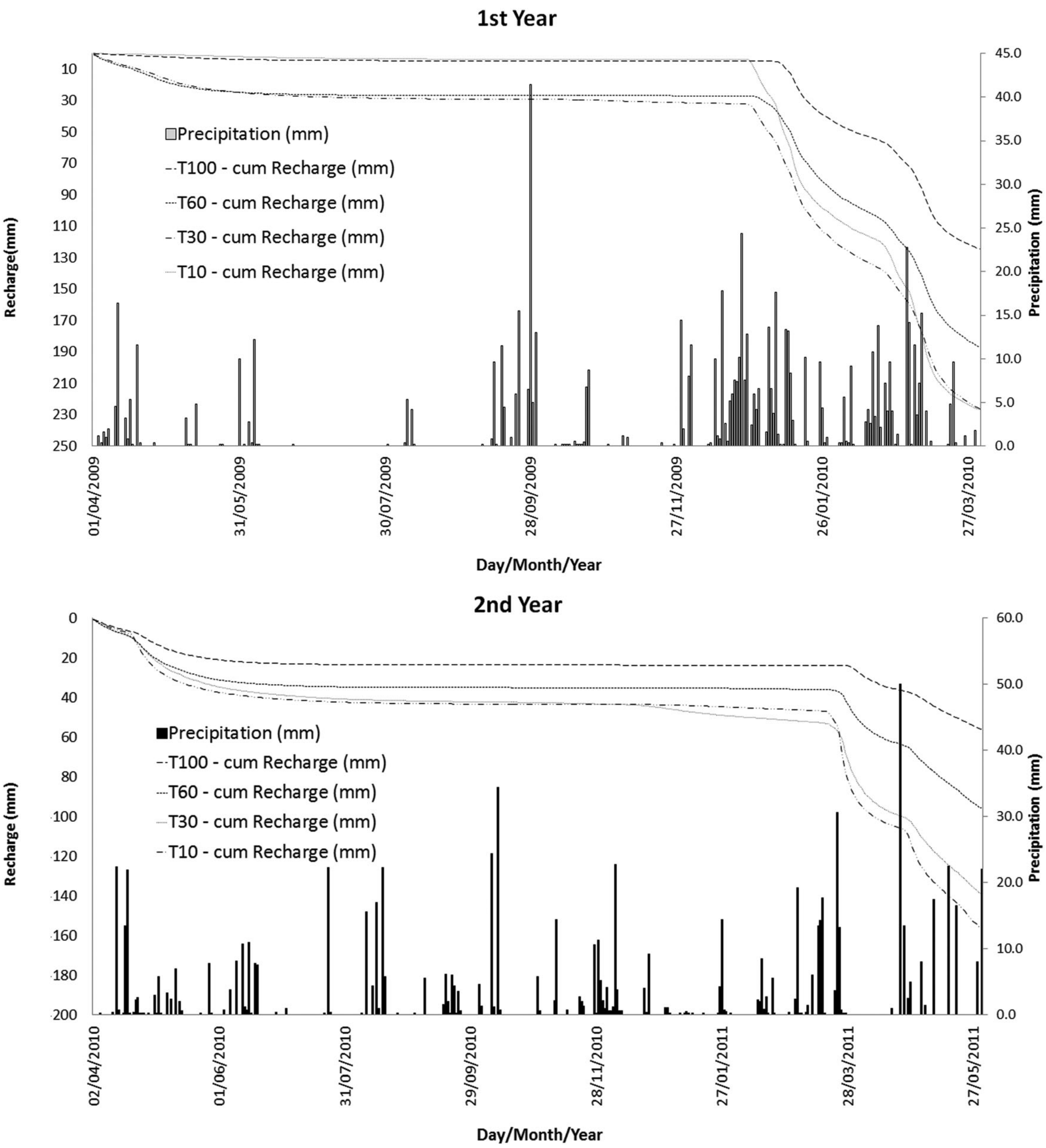

Figure A1. Rainfall and cumulated groundwater recharge during calibration (first year) and validation (second year) periods.

summarized in Table A1. Silvicultural operation consisted of a thinning treatment. Timber and debris were removed and piled outside the plots.

The experimental data on volumetric soil water content (SWC, $m^3 \cdot m^{-3}$) and tree water use (sap flow) taken from the above-cited study and are only outlined here. SWC was continuously measured by FDR sensors (EC-TM, Decagon Devices Inc., Pullman, WA) every 20 min for all treatments during the entire reference period (1 April 2009 to 31 May 31 2011). The field capacity in each treatment was calculated from the average *SWC* readings on three dates when the rainfall depth was higher than 30 mm in the previous 2 days.

Sap flow velocity was measured in the same reference period by the HRM method [*Burgess et al*., 2001; *Hernandez-Santana et al*., 2011; *Williams et al*., 2004] programmed to average the data every hour. The data were converted to sap flow velocity [*Burgess et al*., 2001] and transpiration.

The observed values used in the calibration and validation procedure were the transpiration (T) and soil water content at 30 cm depth (SWC) measured in the experimental plots. Calibration and validation periods

Table A2. Evaluation of Model Performance for Soil Water Content (SWC) and Transpiration (T)[a]

	E		d		d_1		$RMSE$	
Treatment	C	V	C	V	C	V	C	V
T100 (T)	0.40	0.62	0.79	0.86	0.57	0.66	0.21	0.21
T60 (T)	0.53	0.51	0.84	0.83	0.62	0.61	0.14	0.15
T30 (T)	0.35	0.42	0.60	0.84	0.40	0.65	0.14	0.10
T10 (T)	0.60	0.42	0.85	0.83	0.66	0.62	0.15	0.15
T100 (SWC)	0.76	0.52	0.91	0.86	0.75	0.62	0.04	0.03
T60 (SWC)	0.83	0.54	0.94	0.87	0.79	0.70	0.03	0.03
T30 (SWC)	0.68	0.51	0.89	0.82	0.70	0.60	0.04	0.04
T10 (SWC)	0.82	0.67	0.94	0.91	0.77	0.69	0.04	0.03

[a]E = Nash and Sutcliffe efficiency index, d = Willmott's index of agreement, d_1 = modified Willmott's index of agreement, $RMSE$ = root-mean-squared error, C = calibration phase, and V = validation phase.

were evaluated using *RMSE*, *d*, d_1, and *E* model performance statistics. Table A2 summarizes the obtained results of those statistics, and shows a good agreement between measured and modeled values in both calibration and validation periods.

The results obtained are in agreement with other similar works, e.g., *Chen et al*. [2014]. Transpiration is a difficult type of measurement to obtain and with higher uncertainty than soil water content. However, it has

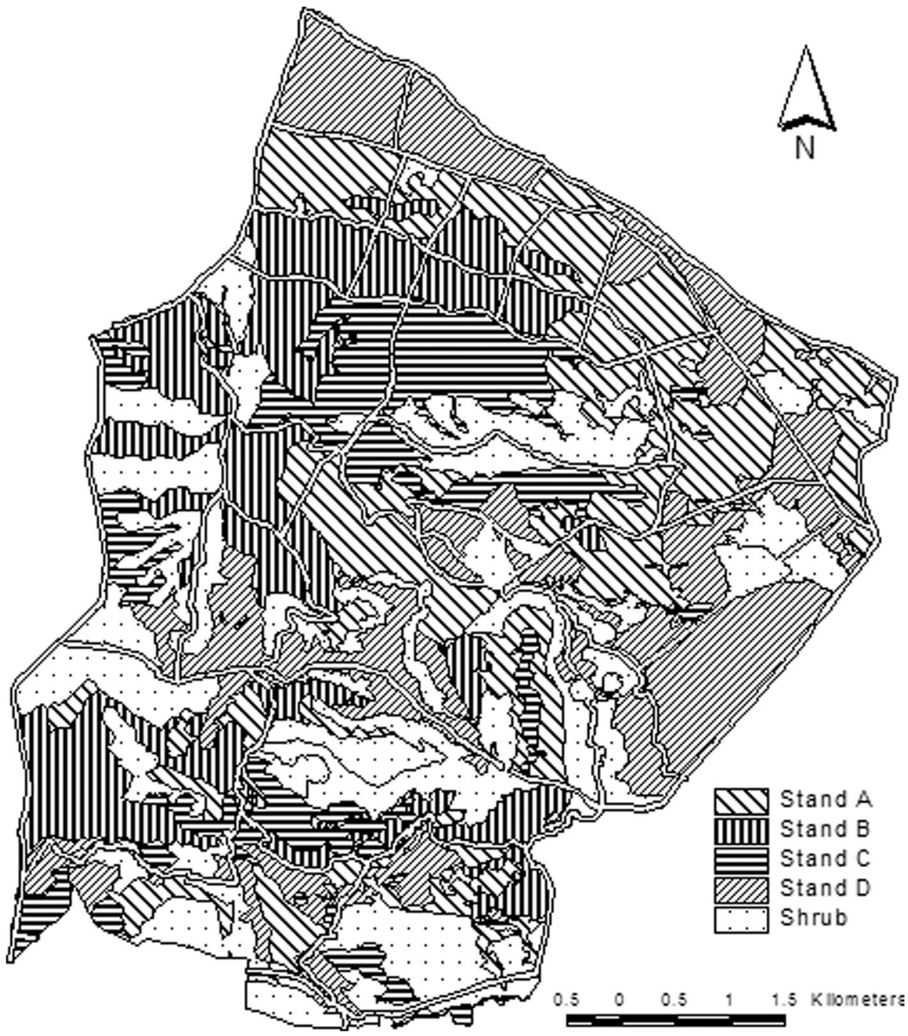

Figure A2. "La Hunde" public forest.

been demonstrated that it is possible to reproduce the soil water content pattern with inverse modeling, accomplishing a very low accuracy in T and ET determinants when they are not included as observed values [*Jhorar et al*., 2004]. By including SWC and T in the calibration and validation procedure, a very good SWC pattern has been obtained and also an acceptable T pattern, derived from the uncertainty in the measurement method.

Cumulated groundwater recharge during the calibration and validation period was represented together with rainfall in Figure 1. As can be seen in Figure 1, groundwater recharge depends on the canopy cover (treatments) and the amount of precipitation, but the effect of canopy cover disappears when it reaches a certain value: in this case, T30 treatment with 50% of canopy cover and T10 treatment with 22% of canopy cover produce similar groundwater recharge. The explanation of this should be that interception when canopy cover is less than 30–40% is negligible. With this consideration in mind, silvicultural operations have been established as follows: when an intervention is decided, silvicultural operation changes canopy cover from its value to 30%.

This behavior is in agreement with the experimental data gathered in the study site [*del Campo et al*., 2014], where maximum groundwater recharge took place when two effects matched at the same time: significant amounts of precipitation in a short period of time together with a dormancy period. The more physiological activity (transpiration), the more precipitation is required to recharge. It should be noted that the behavior of groundwater recharge is in agreement with those observed in many investigations around the world in arid and semiarid forested areas and compiled in *Scanlon et al*. [2006]. Comparing the groundwater recharge for different land use and land covers, they found cases in which recharge in nonvegetated areas was up to 87 mm yr^{-1} and no recharge took place in vegetated areas [*Gee et al*., 1994; *Wang et al*., 2004; *Scanlon et al*., 2005]. This sensitivity of recharge to land use/land cover changes suggests them that recharge may be controlled through management of vegetation.

A2. Case Application Forest Inventory

The experimental plots described in Table 1 were used to calibrate and validate the HYDRUS model in order to obtain the groundwater recharge function. Once this function was obtained, a proposed modeling framework was applied to the whole forest of 3090 ha ("La Hunde" public forest), to which these plots belong. The whole forest comprises four stands with different structures as described in Table 1. A, B, and C stands were uneven-aged stands. D stand was the only even-aged stand in the forest management unit. Spatial distribution of the stands in the management unit can be seen in Figure 2. Since there was a forest inventory [*Calabuig-Vila*, 2012], the canopy cover dynamics was modeled using the actual basal area (BA), even in the D stand. The inventory was summarized in Table A1.

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