

An actionable hydroeconomic Decision Support System for the assessment of water reallocations in irrigated agriculture. A study of minimum environmental flows in the Douro River Basin, Spain

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ARTICLE INFO

Keywords:

Socio-hydrology
Decision Support Systems
Mathematical programming
Environmental flows
Water scarcity

ABSTRACT

Despite major recent advances in socio-hydrology and hydroeconomics research, interdisciplinary methods and models for water policy assessment remain largely concealed to the academic arena. Most river basin authorities still base decision-making on inputs from hydrologic Decision Support Systems (DSS), and have limited information on the economic costs that water policies may impose on the economy. This paper presents a time-variant hierarchical framework that connects a hydrologic module and an economic module by means of two-way feedback protocols. The hydrologic module is designed to fit the AQUATOOL DSS, the hydrologic model used by Spanish river basin authorities to inform decision-making at a basin scale; while the economic module is populated with a Positive Multi-Attribute Mathematical Programming (PMAMP) model that represents the behavior and adaptive responses of irrigators. The proposed hierarchical framework is used to assess the economic repercussions of strengthening irrigation quotas so to achieve minimum environmental flows in the Douro River Basin (Spain) under climate change. Results show that reductions in agricultural water allocations to meet environmental flow requirements create nonlinear incremental profit and employment losses in irrigated agriculture that are on average low to moderate (between -4% and -12.9% for profit, and between -4.6% and -12% for employment, depending on the scenario). During extreme droughts, the abrupt reductions in water availability and agricultural allocations can test farming systems past the breaking point and lead to catastrophic profit and employment losses ($>80\%$).

1. Introduction

Growing human water demands and the water works built to meet them have affected the magnitude, frequency, duration, timing and rate of change of natural flows, threatening the integrity of critical ecosystems and the environmental and socioeconomic services that depend on them (Díaz et al., 2019). This process is particularly severe in over-allocated water basins, where water supply is insufficient to accommodate additional demands and new economic extractions come at the expense of reduced water allocations for competing uses—typically the environment (Tonkin et al., 2018). Overallocation is compounded by shifting precipitation patterns due to climate change, which cause reduced water supply and more intense and frequent droughts that further constrain environmental water uses (IPCC, 2018). In this context, achieving sustainable economic growth necessitates water

reallocations that curb water withdrawals and restore the balance between supply and demand (e.g., through quotas, charges, markets, insurance, payment for ecosystem services, subsidies, voluntary agreements). Given that agriculture represents 70 % of global water withdrawals (FAO, 2021a), which contribute to less than 7 % of the world's Gross Domestic Product (World Bank, 2020), attempts to mitigate supply-demand imbalances often target this sector (Sabo et al., 2017). Yet, despite its relatively low returns from water as compared to other economic sectors, irrigation is a fundamental source of income and employment in rural areas throughout the world, and produces 40 % of the global food production with just 17 % of the total agricultural land (FAO, 2021b). Against this backdrop, several institutions have called for the integration of economic analyses in the design and assessment of water reallocation policies, so to better understand and manage their effectiveness and costs (see e.g. EEA, 2020).

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<https://doi.org/10.1016/j.jenvman.2021.113432>

Received 5 March 2021; Received in revised form 27 July 2021; Accepted 28 July 2021

Available online 3 August 2021

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The ecological, hydrologic and economic literature reports significant advances in the modeling and design of water reallocations, the assessment of their effectiveness in restoring and/or conserving ecosystems and their services, and the assessment of their economic impacts. Hydrology and hydraulics are typically used to understand and predict the repercussions of alternative reallocation mechanisms on the water system dynamics, for which a wide array of models and methods is available (for a review on the methods and models for environmental flows analysis, see e.g. Poff and Matthews, 2013; Richter and Thomas, 2007; Sabo et al., 2017). Hydrologic/hydraulic models and methods can be also used in combination with ecological models that examine changes in the habitat of a selected group of species as a function of hydrologic variables such as discharge (Arthington, 2012; O'Brien et al., 2018; Poff and Zimmerman, 2010; Tonkin et al., 2018). This allows researchers to understand the effectiveness of water reallocations in reverting anthropogenic-induced harm to the environment and critical ecosystem services. Finally, a number of studies have developed methods to integrate socioeconomic aspects into the analysis of water reallocations that allow the assessment and quantification of their economic impacts (Adamson and Loch, 2017; Crespo et al., 2019). In this vein, it is worth mentioning the contributions made from the discipline of socio-hydrology, the science of water and human systems and their interrelationships (Sivapalan et al., 2012). As opposed to conventional static, scenario-based approaches to human-water systems modeling, which are increasingly unrealistic in the Anthropocene (particularly for long-term assessments), socio-hydrology aims to “observe, understand and predict the co-evolution of coupled human-water systems” through the explicit representation of the two-way feedbacks between them (Sivapalan et al., 2012). Over the last decade, an expanding body of socio-hydrology-inspired literature has addressed the multi-faceted problems of human-water systems management (Pande and Sivapalan, 2017), including environmental flows (Essenfelder et al., 2018; Pérez-Blanco et al., 2021a).

However, despite major advances in socio-ecology and socio-hydrology research, interdisciplinary methods and models are mostly concealed to the academic arena, and their uptake by decision makers for effective policy making remains limited (Blair and Buytaert, 2016; Li et al., 2020). Most river basin authorities still base their water reallocation assessments and interventions on inputs from Decision Support Systems (DSS) based on hydrologic models, sometimes developed in combination with habitat models, which typically do not incorporate economic analyses (Bussetini et al., 2015; Crespo et al., 2019; Linnan-saari et al., 2012).

The disconnection between the significant advances in interdisciplinary socio-ecological and socio-hydrology research and the intra-disciplinary focus adopted in empirical water reallocation assessments and interventions is often attributed to resource constraints (time, financial, human, know-how) (Driscoll et al., 2011; Nkiaka and Lovett, 2019). Developing, understanding and processing accurate hydro-economic data for the assessment of complex human-water systems requires careful, long-term water measurement and monitoring, expertise in river basin dynamics, rigorous economic theory and analysis, as well as strong inferential capacity. In practice though, time, human, financial and other resource constraints often mean that the breadth and scope of the performance assessments conducted by river basin authorities are adapted to the available expertise and resources—rather than the other way around. As a result, performance assessments typically adopt a pragmatic hydrologic (and ecological) focus that better fits the expertise (engineering technicians) and resources (software/DSS, data, others) available in river basin authorities. In those rare cases where economic analyses are implemented, these are typically conducted independently from conventional hydrologic assessments, often considering different (if not straightaway incompatible) initial conditions and scenarios (Bussetini et al., 2015; EEA, 2020), and ignoring the relevant two-way feedbacks between human and water systems (Blair and Buytaert, 2016; Pande and Sivapalan, 2017).

In this context, the development of new methods and applications that more effectively integrate state-of-the-art economic theory and modeling into the hydrologic DSS used by river basin authorities is timely. To that end, several authors have proposed the use of hierarchies of models that respond progressively to the scale of the analysis, budgets, capacity, and timeframes of the river basin authority or competent body (Acreman and Ferguson, 2010; Essenfelder et al., 2018; Sivapalan et al., 2012). As opposed to holistic approaches that fully integrate all relevant systems into a single model, model hierarchies represent complex socio-ecological systems by relating its behavior to that of individual system models that are subsequently interconnected. Hierarchical frameworks thus offer a more plausible, realistic and efficient approach to address the application of the interdisciplinary research and methods required to develop thorough and comprehensive water reallocation assessments. Hierarchical frameworks have the additional advantage of being amenable to experimental manipulation that addresses critical socio-hydrology challenges, including: (1) the representation and study of the *two-way feedbacks* between human-water systems; (2) the representation of the time-variant/dynamic co-evolution of human and water systems, so to assess how human behavior affects water bodies and water allocation now and in the future; and (3) the representation and study of how isolated human actions transcend the local scale and have repercussions at the relevant *basin scale*; all of which are “necessary steps in the evolution of science” and policy to face up the growing challenges posed by increasing water scarcity (Pande and Sivapalan, 2017).

This paper uses a socio-hydrology inspired, dynamic, protocol-based modular approach to create a hierarchical framework that interconnects economic and hydrologic modeling by means of two-way feedbacks, so to produce actionable science that can be readily used to inform on the hydrologic and economic impacts of water reallocations at a basin scale. The framework is populated with a Positive Multi-Attribute Mathematical Programming (PMAMP) model that reproduces the behavior and adaptive responses of irrigators (microeconomic module) (Gutiérrez-Martín and Gómez, 2011); and the hydrological DSS AQUATOOL, the DSS used by Spanish river basin authorities to inform decision-making at a basin level (hydrologic module) (Andreu et al., 1991). While AQUATOOL has been widely used to conduct performance assessments of water policies this research is the first that couples AQUATOOL with a full-fledged economic model of human agency. The coupling between the PMAMP and AQUATOOL models is sequential and dynamic and works through protocols, i.e. “rules designed to manage relationships and processes between modules” (Csete and Doyle, 2002). Protocols connect the economic and hydrologic modules through common water allocation and effective water use variables: AQUATOOL provides information on the impacts of physical shocks and restrictions (e.g. droughts, environmental flows) on water allocations for irrigation of relevance for the PMAMP model; while the PMAMP model assesses irrigators’ responses to water allocations or other (physical, economic) shocks, and provides information on effective water use of relevance for AQUATOOL. The modular approach adopted thus allows for iterative feedbacks between the two models and makes possible to simulate the dynamic co-evolution of human-water systems. The coupled AQUATOOL-PMAMP model was developed at the request of the Douro River Basin Authority with funding from the Spanish Ministry for the Ecological Transition, and is illustrated accordingly with an application to the Douro River Basin in Spain, where we assess the economic repercussions of environmental flows under climate change.

2. Background to the case study: minimum environmental flows in the Douro River Basin, Spain

In compliance with the Water Framework Directive (WFD) that aims to achieve the “good ecological status” of water bodies (OJ, 2000), the European Commission published in 2015 a guidance document for the implementation of environmental flows in all EU basins by 2021

(Bussettini et al., 2015). Also in compliance with Art. 5 of the same WFD that calls for “economic analyses of water use” (OJ, 2000), the guidance reminded Member States of their commitment to conduct economic assessments of costs alongside hydrologic and ecological studies, so to identify economic repercussions of environmental flows, inform strategies for the mitigation of negative economic and distributive impacts, and identify potential exemptions where the costs of implementing environmental flows were disproportionate. Environmental flows have been extensively studied in countries like Spain, albeit most studies focus on the ecological and hydrological components so to estimate environmental flows (Alcázar and Palau, 2010; Mezger et al., 2019, 2021), assess the connections between environmental flows and sediment dynamics (García de Jalón et al., 2016), or design pulse flows (Gómez et al., 2014; Magdaleno, 2017). Accordingly, despite calls from EU and national institutions and the significant advances in the scientific literature towards the integration of human-water systems, EU river basin authorities still base their planning and decisions on standalone hydrologic models/DSS, thus being largely oblivious to the economic costs that environmental flows may impose on the economy.

Against this backdrop, the Douro River Basin in Spain is pioneering the integration of the economic analysis of environmental flows into river basin planning and decision-making. The Douro River Basin is the largest basin in the Iberian Peninsula, draining most of the northern portion of the central Iberian plateau. The Spanish part of the Douro River Basin comprises an area of 78,886 km², which roughly matches the area occupied by the Spanish region (NUTS¹) of Castile and León. The Douro River Basin has been traditionally regarded as a water abundant area by Spanish standards, but water scarcity is growing. The average annual water supply is decreasing due to climate change and has been estimated at 12 311 million m³ for the period 1980–2018, –7.5 % as compared to the average annual water supply of 13 308 million m³ for the period 1940–2018 (DRBA, 2016a; MAGRAMA, 2017). On the other hand, annual water withdrawals from consumptive uses, which have experienced a significant increase over the past two decades, are estimated at 3446.9 million m³ (DRBA, 2016a). Accordingly, the Water Exploitation Index (ratio of freshwater withdrawals to the renewable resources available in the basin) is estimated at 34.1 %. This means that the basin is beyond the water scarcity threshold (set at 20 %) and close to the severe water scarcity threshold (40 %) (EEA, 2016). The frequency and intensity of drought events is also increasing, causing significant impacts on the environment and economic uses.

In compliance with the Spanish Hydrological Planning Instruction (BOE, 2008), the Douro River Basin Authority is set to define minimum environmental flows, maximum environmental flows, change rates, and high flows. Since early in the first EU planning cycle (2009–2015), the Douro River Basin Authority has designed and adopted monthly minimum environmental flows for all rivers in the basin, albeit progress in the definition of maximum flows, change rates, and high flows, has been limited.² Minimum environmental flows in the Douro River Basin represent 21 % of the mean annual runoff, and the intra-annual variability of the minimum environmental flows ranges between 7 % and 37 % of the intra-annual variability of unregulated flows (Mezger et al., 2019). Lack of high flows and insufficient change rates are related to habitat loss, which has led to institutional calls to calculate and apply these variables (Magdaleno, 2017). If finally implemented, change rates and high flows will likely increase the cost of environmental flows; thus, our application to minimum environmental flows should be regarded as

a minimum threshold of the costs of environmental flows.

To monitor and enforce compliance, the Douro River Basin Authority has designated a network of control points encompassing 60 river stretches across the basin (DRBA, 2016a, 2012). Discharge data at the designated control points shows a “satisfactory performance” (DRBA, 2020) with limited infringements of the minimum thresholds. This will likely change under future climate, which will exacerbate water scarcity and droughts and is expected to increase the number and intensity of (minimum) environmental flow infringements over the next decades (MAGRAMA, 2017). Moreover, it has been consistently reported that even when minimum environmental flows are observed in the control points, nearby river stretches located upstream/downstream can present flow levels that are “low or very low” (DRBA, 2020). This suggests that control points are too sparse in some areas of the basin, which has propelled the Douro River Basin Authority to revise and increase the number of control points in the new Douro River Basin Plan that will be adopted in 2021.

The more stringent enforcement of minimum environmental flows under climate change is expected to have non-trivial impacts on the agricultural sector, a low priority use (i.e. the first one to experience water restrictions under drought/scarcity conditions) that represents 89.4 % of total water withdrawals for consumptive use in the basin. Due to growing scarcity and environmental constraints, farmers in the region will be increasingly constrained to shift their crop portfolios towards less water intensive or straightaway rainfed crops, which yield a lower economic return. This will be compounded by increasingly frequent and intense drought events, which are expected to lead to abrupt economic losses (IPCC, 2018). Agricultural losses have important ramifications over the economy of the Douro River Basin (Parrado et al., 2020), which is highly dependent on agriculture. Agriculture employs 10 % of the total workforce of Castile and León (Spanish average: 5 %) and produces 5.5 % of its GDP (Spanish average: 2.7 %) (INE, 2019). More than 50 % of the Douro River Basin’s territory is farmland (a 5 783 831 ha equivalent), and the most relevant crops are cereals (notably wheat, barley, rye and oats), legumes (carob, chickpea), sunflower and vineyard (see Table 1). About 9 % of these 5 783 831 ha or agricultural land are irrigated, and divided into 150 Agricultural Water Demand Units (AWDUs), the basic irrigation unit in Spain which comprise “groups of irrigators sharing a common source of water, territorial, administrative, and hydrological characteristics” (Fig. 1—see also Annex IV for a list of the AWDUs). AWDUs are the agents in the PMAMP model.³

Given the economic relevance of agriculture for the Douro River Basin, a major concern for the river basin authority is to be capable of anticipating and better understanding the economic impacts of water reallocations from irrigation to the environment. Obviously, such impact is conditional on the instrument that is used to articulate the reallocation from agricultural to environmental uses. In our case, and at the explicit request of the Douro River Basin Authority, this is done by reducing irrigation water quotas and reallocating the excess water supply to the environment. Quotas are by far the most widely used instrument to reallocate water resources among users in Europe (Rey et al., 2019), including to achieve (minimum) environmental flows (Bussettini et al., 2015); although they are not the most efficient way to do so (Gómez et al., 2017). Alternative reallocation mechanisms such as markets (through buyback) and charges can achieve similar objectives at a lower cost, while enhancing economic efficiency. In this vein, Art. 9

¹ The Nomenclature des Unités Territoriales Statistiques (NUTS), is “a hierarchical system for dividing up the economic territory of the EU” (Eurostat, 2020). In Spain, NUTS 2 refers to regions.

² Pilot pulse flows have been designed and tested for a number of sub-basins across the Douro River Basin, although their development is still in a preliminary phase that will not be concluded until the next planning cycle (2021–2027).

³ The aggregation of individual farmers to conform representative economic agents is well documented in the literature. In the case of Spain, aggregation is often done at the level of Water User Associations WUAs (García-Mollá et al., 2013), agricultural districts (Gutiérrez-Martín and Gómez, 2011) or AWDUs (Calatrava and Martínez-Granados, 2012). Here we work with AWDUs as the relevant aggregation unit for our coupled model due to two reasons: 1) AWDUs are the relevant aggregation unit for water allocation decisions; and 2) AWDUs are the aggregation unit used by AQUATOOL.

Table 1

Agricultural land use in the Castile and León Region – irrigated and rainfed crops. The irrigated farmland (AWDUs) is highlighted in bold letters. Own elaboration from ITACyL (2019).

Crop	Irrigated area (ha)	Rainfed area (ha)
Wheat	39,577	765 960
Barley	23,361	677 675
Oats	6461	42 699
Rye	2491	57 075
Triticale	1302	17 992
Corn	116,667	
Forage corn	7323	72
Apple tree	1525	
Green pea	2534	
Potato	17,614	
Carrot	6003	
Vineyard	3296	59,703
Sunflower	16,300	184,649
Olive tree	943	2777
Sugar Beet	24,744	
Alfalfa	39,737	43,889
Vetch	1836	37,354
Forage vetch	3578	49,556
Pea	1475	35,239
Lentils		3936
Chickpeas	516	5968
Lupine		3106
Carob		1417
Hop	942	
Rapeseed	5276	14,218
Walnut	446	310
Almond	600	3300
Lettuce	710	
Spinach	576	
Green chicory	468	
Pumpkin	630	
Garlic	2581	152
Onion	2931	
Leek	1837	
Green peas	2534	

of the WFD states that “[...]water-pricing policies provide adequate incentives for users to use water resources efficiently, and thereby contribute to the environmental objectives of this directive” (OJ, 2000, art. 9) through the recovery of financial (cost of infrastructures and services for supplying water), resource (“the costs of foregone opportunities which other uses suffer due to the depletion of the resource beyond its natural rate of recharge or recovery”) and environmental costs (“the costs of damage that water uses impose on the environment and ecosystems and those who use the environment”) of water use from those responsible for causing them (WATECO, 2003). If full cost recovery was to be pursued through charges, the approach adopted by the river basin authority to achieve minimum environmental flows should be updated accordingly: from assessing the economic costs of agricultural quotas towards achieving environmental flow targets, to measuring and *recovering* the economic costs of observed reductions in environmental flows attributable to economic uses (which would lead to reduced economic uses, and increased environmental uses). However, measuring the environmental costs of economic uses necessitates thorough knowledge of the society’s demand function for environmental water (so to quantify the economic value of foregone environmental water uses, or environmental cost), and eliciting such function is far from simple. First, it is difficult to predict the physical impact that reductions in (minimum) environmental flows have on the ecosystem services that society puts value upon (Chaikaew et al., 2017); Second, “there are few standardized approaches to measure the economic value of that impact, whether within or between sectors [...], and there are often large differences between values obtained through different methods” (UN, 2021). Accordingly, although some recent contributions have proposed methodologies to bridge this gap (Chaikaew et al., 2017; García de Jalón et al., 2017), there is no consensus yet on how to

estimate the environmental cost of the economic uses of water. As a result, while water charging has been extensively used as a financial instrument in the Douro River Basin and elsewhere in Europe (i.e., to recover the construction and maintenance costs of water infrastructures, albeit not fully), the recovery of environmental and resource costs has been largely neglected (Dinar et al., 2015). Charges can also be technically unfeasible, e.g. due to the lack of metering devices at field scale or the nature of some agricultural systems (metering large quantities of water flows across rice fields through the saturated zone is currently not possible) (Dinar et al., 2015). On top of this, charges typically face considerable opposition and high transaction costs (Garrick et al., 2013; Santato, 2018). These challenges justify the use of alternative policies by river basin authorities, notably quotas.

Quotas are less technically complex to design and apply (e.g., they do not rely on accurate estimates of the price elasticity of demand). By imposing a proportional cap on users, quotas can also better address equity issues that arise from the asymmetric ability to pay of irrigators, where some users can afford charges and some others cannot. Quotas typically face less opposition by affected water users than charges, which reduces the political and transaction costs of policy reform. Although quota-based systems also face significant challenges, notably regarding their effectiveness (e.g., irrigators can react to irrigation rationing on certain days of the week by increasing water use during unrestricted days), they are the predominant instrument in the European context to implement environmental flows—and the one chosen by the Douro River Basin Authority to meet minimum environmental flow targets (DRBA, 2020).

3. Methods: a socio-hydrology-inspired protocol-based modular framework

3.1. Positive Multi-Attribute Mathematical Programming (PMAMP)

The behavior of agricultural agents and their responses to changes in water or agricultural policies are typically assessed through structural microeconomic models that incorporate the “deep parameters” or microfoundations (relating to preferences, technology, and resource constraints) driving human responses to change. Structural microeconomic models are mathematically stated representations of human agency that are calibrated to mimic the observed behavior of economic agents, and can be used to understand key behavioral drivers and predict responses to exogenous shocks. The range of plausible responses is limited by a domain $F(x)$ conformed by a set of physical and socioeconomic restrictions (Graveline, 2016). Agents in the models are assumed to be rational, i.e. they allocate available production inputs (in our case, through a decision on land use, x) so to maximize the economic return within the domain, where the economic return is measured through a utility function $U(x)$ conformed by one (single-attribute) or multiple (multi-attribute) utility-relevant attributes $z(x)$ (e.g. profit, risk avoidance):

$$\text{Max}_x U(x) = U(z_1(x); z_2(x); z_3(x) \dots z_m(x)) \quad [1]$$

$$\text{s.t.: } 0 \leq x_c \leq 1 \quad [2]$$

$$\sum_{c=1}^n x_c = 1 \quad [3]$$

$$x \in F(x) \quad [4]$$

$$z(x) \in R^m \quad [5]$$

where x is the decision variable or crop portfolio, a vector indicating the share of land used by each crop x_c , which is revised on a yearly basis (irrigation campaign). Each crop x_c delivers a unique combination of

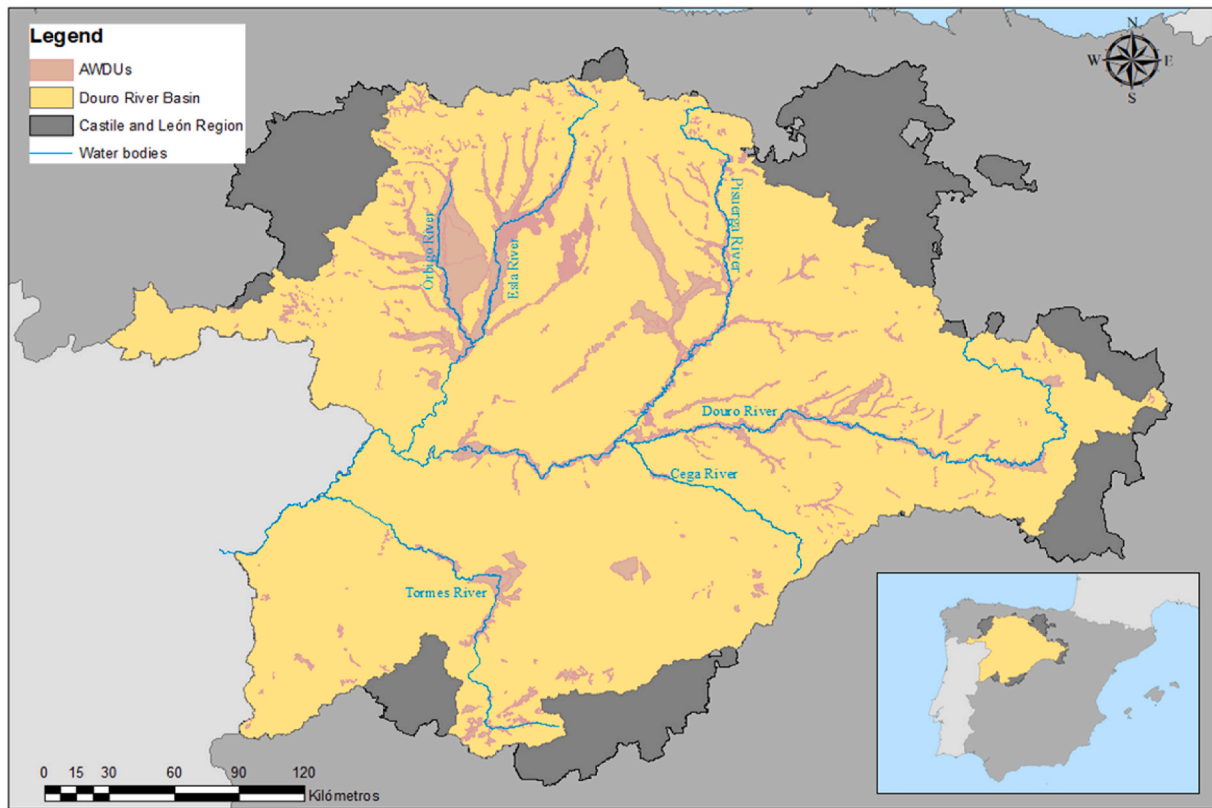


Fig. 1. Location of the Douro River Basin in the Iberian Peninsula and detail of its AWDUs. For a complete list and description of the AWDUs, the reader is referred to Annex IV in the online supplementary material.

utility-relevant attributes $z(x_c)$ $z(x_i)$. $F(x)$ represents the set of constraints that conform the domain, including the water allocation constraint, of particular relevance for our research:

$$\sum_{i=1}^n w_i x_i \leq W \quad [6]$$

where w_i represents the beneficial consumption/evapotranspiration by crop c ; eff_c represents irrigation efficiency; $\frac{w_c}{\text{eff}_c}$ is the water application needs (i.e. including beneficial and non-beneficial consumption and return flows); W represents the water allocation constraint (per hectare), i.e. the amount of water that is assigned to each AWDU in a given irrigation campaign; and $\sum_{c=1}^n \frac{w_c}{\text{eff}_c} x_c$ represents the effective water use.

Agents can reduce $\frac{w_c}{\text{eff}_c}$ by shifting to more efficient irrigation systems that increase irrigation efficiency.

The attributes in the utility function and their parameter values can be elicited using normative methods based on value judgements by experts (e.g. the agent aims to maximize total profit); or positive methods that use mathematical programming models to identify the utility-relevant attributes and calibrate the parameters that more accurately reproduce observed decisions. Mathematical programming models are more frequently used, and include Linear Programming and Positive Mathematical Programming (single-attribute); and PMAMP (multi-attribute), which is the model used in this paper (for a review see e.g. Sapino et al., 2020). Note that our approach is flexible and alternative single- and multi-attribute utility functions and models could be used to replace the PMAMP model in our coupled model. The choice of a multi-attribute utility function and PMAMP model is pragmatic and driven by the previous experience of policy makers in the basin with the use of these microeconomic models (Parrado et al., 2020; Pérez-Blanco et al., 2021b).

A comprehensive description of the microeconomic model and the

PMAMP calibration method is available in the literature (see e.g. Essenfelder et al., 2018) and in the online supplementary material, which includes the mathematical formulation of the domain $F(x)$ (Annex I); the PMAMP calibration method (Annex II); the attributes explored, which include expected profit, risk avoidance and management avoidance (of which the latter is measured through three proxy attributes: total labor avoidance, hired labor avoidance and direct costs avoidance); the related data inputs (Annex III); and the calibration results (Annex IV).

3.2. AQUATOOL

AQUATOOL is a DSS for the edition, operation, review and analysis of hydrologic models for river basin management that produces information on the quantitative and qualitative status of water bodies. The AQUATOOL DSS features a number of modules, each with its own software/model suitable for alternative tasks: AQUATOOL is the general interface for editing data and managing the other modules; SIMGES is the module for simulating watershed management, including conjunctive use; GESCAL is the module for simulating water quality at the basin scale; OPTIGES is the module for optimizing watershed management; SIMRISK is the module for risk assessment and management; EGRAF is the module for the graphical visualization of the results obtained through SIMGES, OPTIGES, GESCAL and SIMRISK; and EXTOPO is the module for exporting spatial data to vector format (PUV, 2020). Our study in the Douro River Basin uses the AQUATOOL (setup) and SIMGES (simulation) modules to conduct a longitudinal and spatial assessment of the impacts of implementing minimum environmental flows, under alternative hydrologic conditions.

The different components of the water system that are incorporated into the AQUATOOL and SIMGES modules include surface water bodies, groundwater bodies, discharge series under natural conditions, river-aquifer interaction, infrastructures (reservoirs, canals, irrigation

systems), water demand units (including AWDUs—the agent in the microeconomic model), conveyance, distribution and application inefficiencies (and related return flows and non-beneficial consumption), evaporation from reservoirs, minimum environmental flows, water rights and water operation rules. All this data is accessible from online databases made available by the Douro River Basin Authority (DRBA, 2016a, 2016b), with the exception of the discharge series under natural conditions, which need to be produced. Discharge series under natural conditions are derived processing daily series of precipitation for the 1950–2015 period using the EVALHID tool, which integrates several rainfall-runoff models (Lerma et al., 2017). The resultant 1950–2015 series is further expanded using data from the SIMPA (*Sistema Integrado para la Modelación del proceso Precipitación Aportación*) rainfall-runoff model for the 1940–1950 and 2015–2018 periods (CEDEX, 2020). Data records from reservoirs and monitoring stations representative of the natural regime were used to address discrepant values.

The impacts of the new minimum environmental flows on *water system dynamics* are assessed through a longitudinal simulation that offers spatial information on surface and subsurface water flows on a monthly basis. For surface water bodies, water flows and stocks are obtained by continuity or balance, while for groundwater bodies this is obtained through unicellular and multicellular models. Next, the management of the water system by the river basin authority that determines *water allocations* among alternative uses (including the environment, i.e. minimum environmental flows) is simulated using a network optimization algorithm. This algorithm determines water allocations across the basin conditional to the achievement of a number of objectives, including: i) meeting minimum environmental flows targets but also ii) minimizing water deficits among uses, iii) achieving a certain water stock in reservoirs and iv) achieving hydropower generation targets. The management algorithm is calibrated using up-to-date data on water rights and observed water allocations among uses, with the objective of matching simulation outputs with the observed discharge and water stock in reservoirs (positive approach) (PUV, 2020). Thus, although one key objective in AQUATOOL is that of enforcing minimum environmental flows, during periods of acute scarcity where there are relevant tradeoffs between this and other objective(s), minimum environmental flow targets may not be fully achieved. For example, the basin authority will not deplete water stock in reservoirs beyond a lower threshold to achieve minimum environmental flows.

Given the applied policy focus of our paper, for all modeling exercises in this paper we built on the latest version of AQUATOOL that was set up and calibrated by the Douro River Basin Authority to inform its 2021 Douro River Basin Management Plan (DRBA, 2020).

3.3. Coupling

This paper adopts a socio-hydrology inspired framework that connects, in a sequential and recursive fashion, a microeconomic and a hydrologic module using bidirectional protocols. The adoption of bidirectional protocols allows the simulation of the two-way feedbacks occurring in human-water systems and their impacts. The coupling is designed to be time-variant, thus making possible to assess the dynamic co-evolution of human-water systems.

We develop two bidirectional protocols connecting human and water systems. In the *first protocol*, information on the water allocation for each agent/AWDU is transferred from the hydrologic to the microeconomic module at the beginning of the irrigation campaign in April. In the *second protocol*, information on the effective amount of water used by each agent/AWDU (a function of the crop portfolio choices, x) is transferred from the microeconomic to the hydrologic module. Note that AQUATOOL runs simulations at monthly time steps, while microeconomic models predict crop portfolios (and related water use) for the irrigation campaign (annual timescale). Thus, in the second protocol the information on aggregate water use in the microeconomic module is distributed over the months of the irrigation campaign. The protocol

sequence is conditional on the type of shock assessed in the model. In our application to minimum environmental flows, the exogenous policy shock first impacts the hydrologic module, which runs a simulation to assess the water allocation for each agent, including AWDUs, in the year t . Next, information on water allocations for each AWDU is conveyed to the microeconomic module, which runs a series of simulations (one per agent/AWDU) to assess agents' crop portfolio responses (and related water use, income, employment, etc.) to year t water allocation constraint. Note that due to preferences and other constraints (e.g. crop rotation), effective water use needs not match the water allocation for all agents and can indeed be lower (meaning Eq. (6) is not binding for some AWDUs). The information on effective water use is then transferred to the hydrologic module in t , and is combined with hydrological input data for the following months to assess the status of the water system in $t + 1$, including water allocation for economic agents. This process is repeated in sequence for a predefined number of years (Fig. 2).

4. Results

4.1. Simulation scenarios

Our simulations use AQUATOOL to estimate the water allocations to irrigators under the minimum environmental flow thresholds proposed in the latest draft of the 2021 Douro River Basin Management Plan (DRBA, 2020), and assess the economic impacts (profit, employment) of strengthening the water allocation constraint (equation [6]) in the agricultural sector through the PMAMP model. Thus, in compliance with the guidance provided by the Douro River Basin Authority, minimum environmental flows are enforced through a reallocation of water uses in which agricultural water uses are capped so to achieve minimum environmental flows targets. Water charges remain the same throughout.

Simulations are run for a 38-year timeframe (1980/1981 to 2017/2018), following best practices established by the relevant Ministry (MAGRAMA, 2017) and adopted by the Douro River Basin Authority, which use a short hydrologic time series that is considered more representative of the current water regime.⁴ New infrastructures (dams, reservoirs, canals, irrigation modernization) were also added to the hydrologic module to account for their impact (see Annex V for a list of the new infrastructures; for a detailed description of these infrastructures, the reader is referred to the draft of the 2021 Douro River Basin Management Plan (DRBA, 2020)). In addition to these common settings, we consider two alternative climate change scenarios that mimic those explored in the 2021 Douro River Basin Management Plan: no climate change v. climate change (RCP4.5, equivalent to an 11 % average reduction in discharge basin-wide) (MAGRAMA, 2017). Finally, we include two alternative settings for the network of control points: current setting that monitors 60 river stretches v. a more comprehensive network of control points that incorporates 91 new river stretches on top of the 60 already monitored (see Annex VI for a detailed description of the monitored river stretches in each scenario). This results in three alternative scenarios (Table 2).

Scenario S_00 captures the current situation, with a network of 60 control points, and where future climate change impacts have not unfolded yet (short run); scenario S_01 assesses the impact of expanding the network of control points to 151 units and in the short run (no climate change); and scenario S_02 assesses the impact of expanding the network of control points to 151 units and in the medium/long run, where the consequences of future climate change unfold. All scenarios

⁴ Although relevant hydrological data is available for the period 1940–2018 (78 hydrological years), hydrological studies in Spain typically use short series starting from 1980 (being 2018 the last year with available data as of February 2021, i.e. 38 hydrological years). This short series is considered more representative of the current water regime, which has been significantly affected by anthropogenic activities.

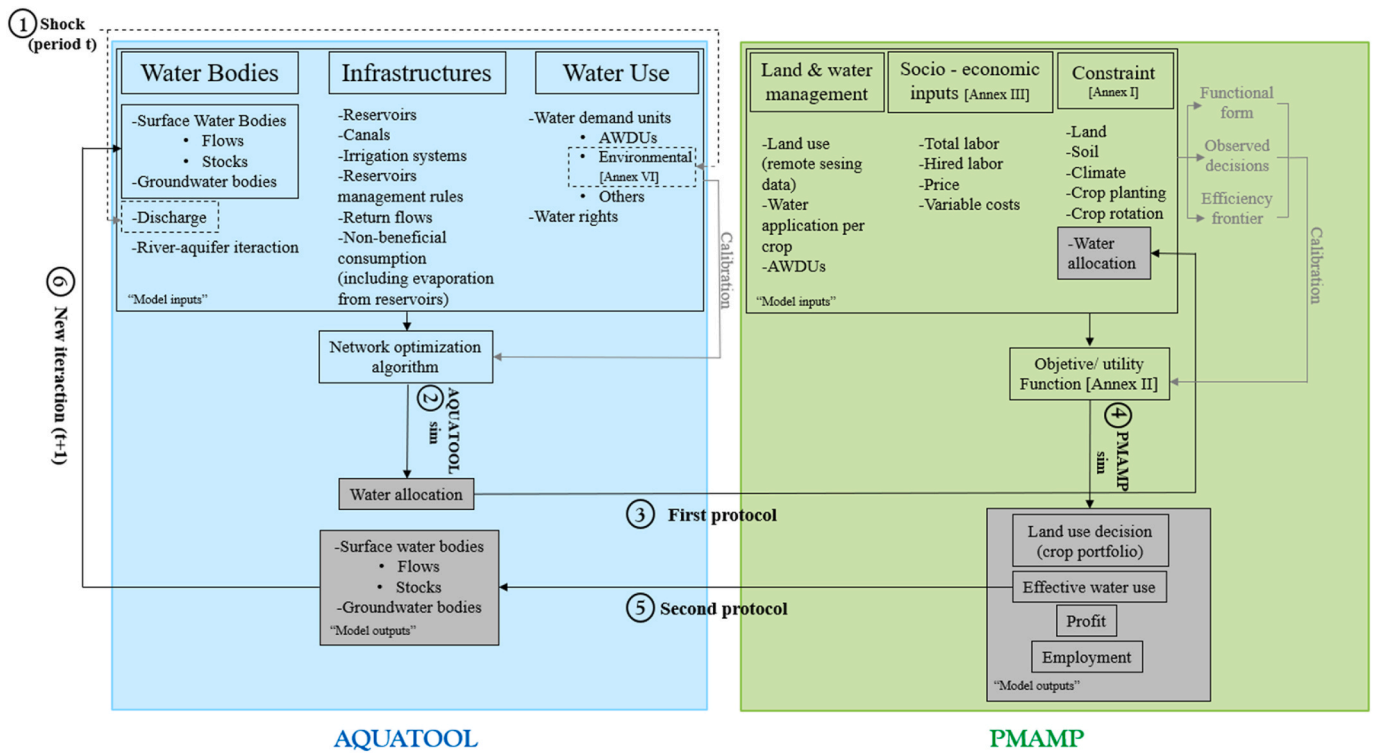


Fig. 2. Conceptual design of the coupled PMAMP – AQUATOOL modeling framework. Step 1 introduces a shock (new minimum environmental flows under climate change), which forces the AQUATOOL model and yields the new water allocations for each AWDU (Step 2). In Step 3, the new water allocation constraints are conveyed to each economic agent/AWDU in the PMAMP model through the first protocol, and a simulation is run to determine land use and water application decisions (Step 4). In Step 5, information on effective water use is conveyed from the PMAMP to the AQUATOOL model through the second protocol, and this information is used to estimate the status of the water system (stock and flows of surface and groundwater bodies). Steps 1 to 5 occur over the same period t . Finally, in Step 6, the status of the water system in t is used as an input to start a new iteration by simulating a new period $t+1$.

Note that the protocol sequence above applies to shocks affecting first the water system. For a shock affecting first the behavior of agents/AWDUs in the human system (e.g. an increase in water charges), the sequence would be different: 1) simulate agents' responses in the microeconomic module; 2) activate the second protocol; 3) simulate impacts on the hydrologic module; 4) activate the first protocol; and 5) repeat the process iteratively. Also note that although the coupling is designed to be flexible and alternative models could be used at the level of each system, the description and conceptual design of the hierarchical framework in the text above and in Fig. 1 is applicable to the PMAMP-AQUATOOL modeling framework. Ad-hoc transformations may be needed to adapt the proposed framework to alternative hydrologic models (the PMAMP model could be replaced by alternative normative, linear programming and positive mathematical programming models without any change to the model setting).

Table 2
Simulation scenarios (S).

Scenario (S)	Minimum environmental flows	Climate change	Control points
S_00	As defined in DRBA (2020)	Not considered	60 river stretches monitored
S_01	As defined in DRBA (2020)	Not considered	91 additional river stretches monitored (151 in total)
S_02	As defined in DRBA (2020)	–11 % average reduction in discharge	91 additional river stretches monitored (151 in total)

were co-designed alongside relevant decision-makers leveraging on two in person meetings with representatives from the Douro River Basin Authority. Other scenarios explored during the meetings (e.g. current network of 60 control points and climate change) were finally discarded by the basin authority, which deemed them less plausible or non-compatible/non-relevant for the interventions considered in the 2021 Douro River Basin Management Plan.

4.2. Simulation results

Leveraging on the coupling framework in Section 3.3 we combine the

AQUATOOL and PMAMP models to assess the foregone profit (gross variable margin) and foregone employment (hours of hired work) that result from the implementation of minimum environmental flows in each scenario, as compared to a normal hydrological year without any reduction in water allocations.

Simulations run as follows. First, the scenarios defined in Table 2 are reproduced in the hydrologic module to assess impacts on the water system, including water allocations for each AWDU based on the AQUATOOL network optimization algorithm. Next, the water allocation in Eq. (6) in the microeconomic module is revised in accordance to the prediction in the hydrologic module for each AWDU, and the agent/AWDU solves the optimization problem in Eqs. (1)–(5) to maximize its utility within the new domain. In those years and for those AWDUs where the water allocation constraint is binding and reduced, the AWDU will have to revise its crop portfolio, leading to a drop in utility and changes in employment and profit. This process is repeated for all years in the hydrologic series and all AWDUs in the basin, which results in a database of simulations including longitudinal (38 years in the short hydrologic series) and cross-section data (150 AWDUs in the basin). Changes in the aggregate crop portfolio (obtained aggregating the land use for each crop category and AWDU) and aggregate water allocation (obtained aggregating the water allocations for each AWDU) in the Douro River Basin for each year in the series are shown in Fig. 3. Changes in land use and in water allocations are measured against a hypothetical counterfactual without water allocation reductions (year

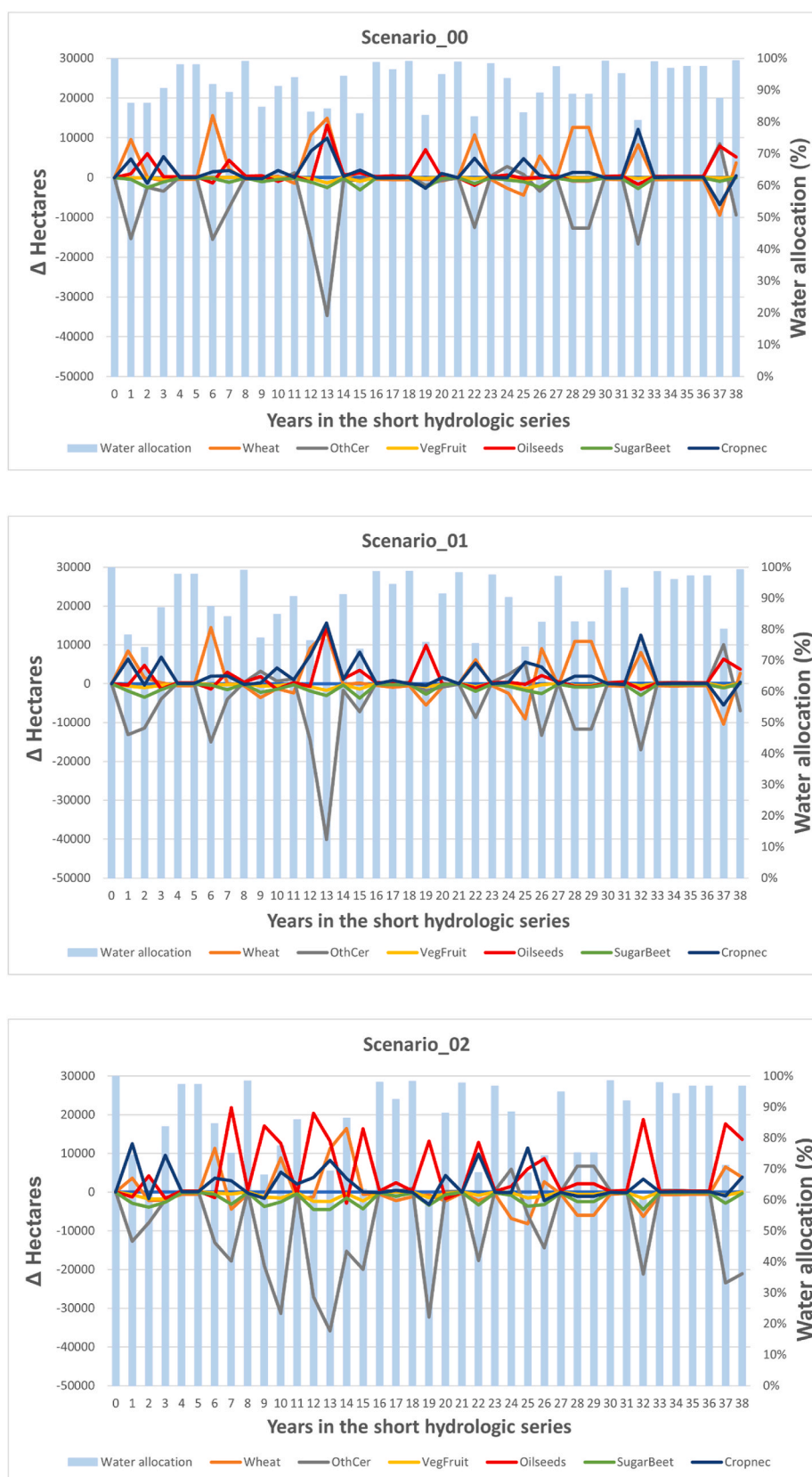


Fig. 3. Changes in aggregate water allocation (%) and aggregate land use (%) across the Douro River Basin. Changes in water allocation and land use are obtained comparing the water allocation and land use values in each year in the series against the water allocation and land use in a hypothetical counterfactual without water allocation reductions (year 0 in the series).

0).

For the sake of simplicity, aggregate crop portfolio changes are presented for six macro-categories instead of individual crops, namely: wheat, other cereals (barley, oats, rye, triticale and maize), vegetables and fruits (potato, lettuce, spinach, green chicory, pumpkin, garlic, onion, leek, carrot, green peas, apple tree, pear tree, almond, walnut and vineyard), oilseeds (sunflower and olive tree), sugarbeet and other crops (*cropnec*, including bean, lentil, chickpea, dried pea, vetch, lupine, carob, hop, rapeseed, forage maize, alfalfa and forage vetch).

The macro-categories include both irrigated and rainfed farmland. Rainfed farmland is marginal in the AWDUs during wet and normal hydrological years, and increases during dry years when water allocations are reduced. It should be noted that changes in the water allocation and crop portfolio can differ, sometimes largely, among AWDUs. Accordingly, the results shown in Fig. 3, while being representative of the trends observed at a basin level, are not necessarily representative of the trends observed in each of the AWDUs within.

Aggregate crop portfolio responses to water allocation reductions are similar for S_00 and S_01. When the water allocation is reduced, the surface of other cereals typically decreases due to the reduction in the surface of irrigated maize; albeit this reduction is in part mitigated by the increase in the surface of rainfed cereals, notably barley (for example, in year 37 the reduction in the surface of maize is more than offset by the increase in the surface of rainfed barley for both S_00 and S_01). The surface of irrigated wheat also decreases during dry years, although its total surface increases because the expansion of rainfed wheat more than offsets the reduction of irrigated wheat. A similar trend to that of wheat is observed for sunflower, whose dryland area increases significantly in most years where the water allocation is reduced. After irrigated cereals, agents start reducing the surface of profitable and

water intensive sugarbeet, followed by vegetables. Finally, the surface of other crops experiences a significant increase during dry years driven by the expansion of rainfed forage crops (mostly alfalfa). Where the surface of other crops decreases, this is the result of the substitution of irrigated alfalfa by crops other than rainfed alfalfa.

In S_02, where climate change is considered, reductions in water allocations are significantly larger than in S_00 and S_01. As a result, the reductions in the surface of sugarbeet and vegetables and fruits, and the increases in the surface of rainfed sunflower, are more pronounced. The reductions in the surface of maize (other cereals), albeit similar in magnitude to those observed in S_00 and S_01 for several of the years in the series, are more frequently observed. This leads to non-trivial economic impacts, as shown in Figs. 4 and 5.

In S_00 (current network of control points and in the short run/without climate change), the average profit and employment basin-wide are estimated at 1327.9 EUR/ha and 1.6 h/ha, respectively. This amounts to a moderate reduction in profit and employment of 4 % and 4.6 %, respectively, as compared to the 1382.9 EUR/ha and 1.7 h/ha that would be attained without any reductions in water allocations (counterfactual in year 0). Transitioning from S_00 to S_01 involves a more stringent enforcement of minimum environmental flows (expanded network of control points), and basin-wide profit and employment decrease on average by 5.8 % and 6.9 %, respectively, as compared to the counterfactual (a 1.8 and 2.3 percentage point increase with respect to S_00). Finally, in S_02 (with the expanded network of control points and under climate change), basin-wide profit and employment losses increase to 12.9 % and 12 %, respectively, as compared to the counterfactual in year 0 (a 8.9 and 7.4 percentage point increase with respect to S_00).

It should be noted that the figures above are aggregate values

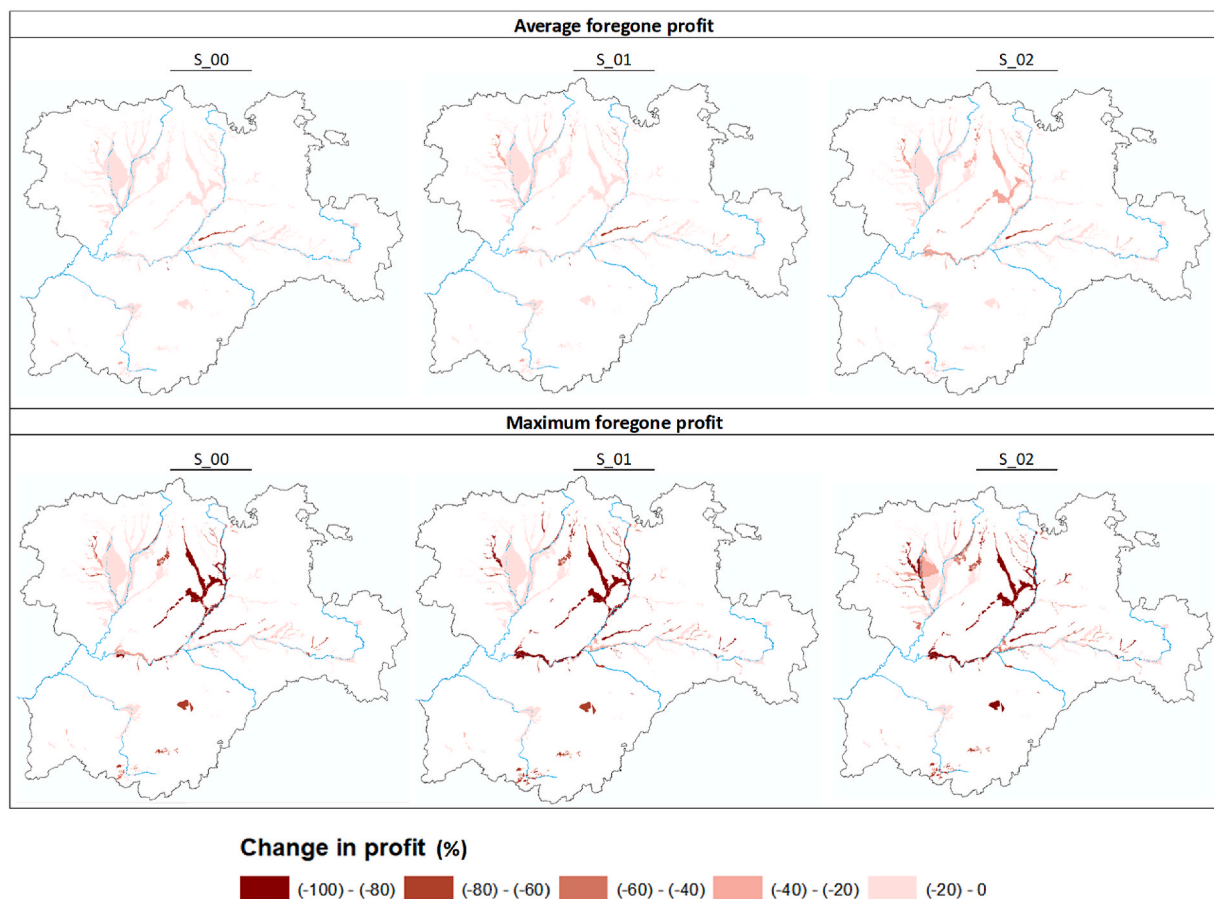


Fig. 4. Economic impacts of minimum environmental flows: foregone profit (%). Changes in profit are obtained comparing the profit in each year in the series against the profit in a hypothetical counterfactual without water allocation reductions (year 0 in the series).

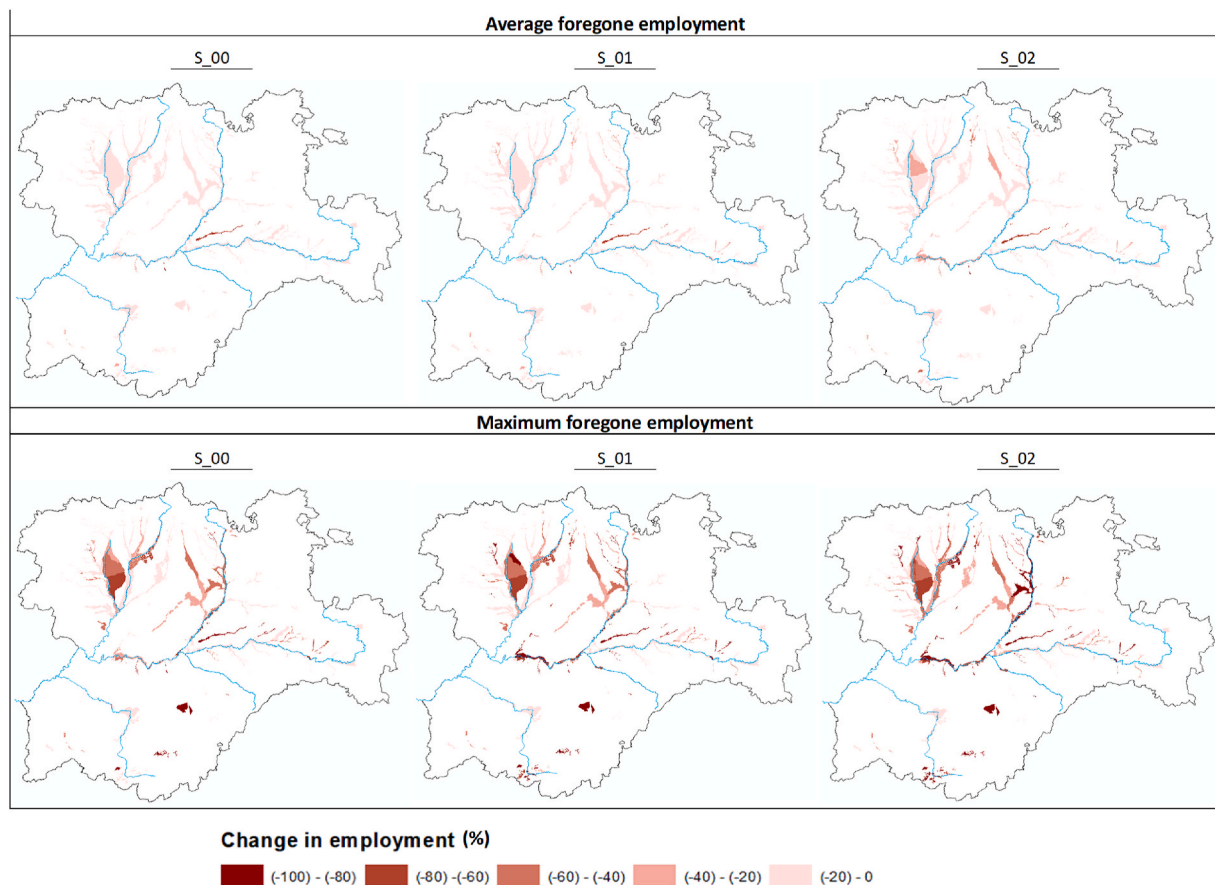


Fig. 5. Economic impacts of minimum environmental flows: foregone employment (%). Changes in employment are obtained comparing employment in each year in the series against employment in a hypothetical counterfactual without water allocation reductions (year 0 in the series).

obtained using a basin-wide weighted average. When we disaggregate the results and focus on the different sub-basins and AWDUs across the Douro River Basin, relevant asymmetries emerge. The most pronounced profit and employment losses are experienced by those AWDUs that are reliant on profitable and water intensive crops (sugarbeet, vegetables and maize), which are typically located downstream (and therefore more exposed to water scarcity and droughts). On the other hand, traditional cereal areas are those least affected in both absolute and relative terms by water allocation reductions, due to the reduced profit and employment gap that exists between irrigated cereals and the best rainfed alternative—which is often the same or a similar cereal. For example, in the cereal-growing AWDUs of the upper Esla River, the average profit loss is below 0.1 % (S_00) and 3.9 % (S_02) and the average employment loss is below 1.4 % (S_00) and 5.6 % (S_02) for all AWDUs. On the other hand, in the AWDUs of the Lower Douro sub-basin, which are heavily dependent on water inflows from upstream basins and have a relatively high share of profitable crops (notably maize and sugarbeet), average profit losses can reach up to 30.4 % (S_00) and 45 % (S_02), and average employment losses up to 41.7 % (S_00) and 59.1 % (S_02).

Finally, economic losses will (significantly) exceed the average values reported above during extreme droughts, when several AWDUs can experience profit and employment losses in excess of 80 %. This outcome is observed in 28 (S_00), 43 (S_01) and 49 (S_02) AWDUs in the case of profit, and in 13 (S_00), 26 (S_01) and 37 (S_02) AWDUs in the case of employment. The maximum foregone profit and employment for each AWDU as compared to the counterfactual (year 0 in the series) are shown in Figs. 4 and 5, respectively.

5. Discussion and conclusions

This paper presents a socio-hydrology inspired, dynamic, protocol-based modular approach to create a hierarchical framework that interconnects human (economic modeling) and water systems (hydrologic modeling). Through interactions between human and water systems, new systemic properties emerge, where the coupled system produces new patterns of behavior over time (coevolution) that differ from those of its individual components alone. The coevolution of the coupled system is characterized by non-linearity, and occasionally results in surprise and crisis. This is illustrated by the rising incremental changes in foregone profit and employment that are observed as we transition from S_00 to S_01 and S_02. AWDUs will initially accommodate reductions in water allocations by substituting irrigated crops at the margin (e.g. wheat) by rainfed crops, while trying to keep the surface of valuable irrigated crops (maize, sugarbeet, vegetables and fruits) stable. If water allocations are further reduced, AWDUs will be constrained to reduce the surface of maize, sugarbeet, vegetables and fruits (usually in this order), and profit will experience more abrupt reductions. Since these crops are also the most labor intensive, employment may be subject to abrupt changes as well. This explains why marginal reductions in water allocation sometimes result in significant, more-than-proportional reductions in profit and employment, leading to a substantial amount of surprise. For example, the AWDUs in the Carrión sub-basin have accommodated current minimum environmental flow thresholds with low to moderate economic losses (average profit and employment reduce by <5 % in S_00), but can experience abrupt reductions in the average profit and employment of up to 40 % under the more stringent enforcement of minimum environmental flows in S_01. Similarly, the AWDUs in the Arlanza sub-basin, which barely experience economic

losses under S_00 (average profit and employment reduce by $<0.5\%$) and S_01 (average profit and employment reduce by $<1\%$), show abrupt reductions in the average profit and employment of up to 12% in S_02. This surprise cannot be captured without economic modeling that represents human agency, and its non-linear responses and interactions with the water system.

This also means that interpreting and comparing the results obtained with the three scenarios considered is far from straightforward. Notably, it is not possible to attribute a specific impact on employment or profit to the different variables (climate change, minimum environmental flows) explored in the scenarios. For example, it would be incorrect to assume that implementing the expanded network of control points in S_01 increases profit losses in the Douro River Basin by 1.8 percentage points and that climate change in S_02 further increases profit losses by an additional 7.1 percentage points, because the effects accumulate in a nonlinear and more-than-proportional fashion. If we altered the order of the scenarios (first applying climate change, and then adding the new network of control points on top of it), the impact of the new network of control points on profit and employment would be higher, since it would affect more valuable and labor-intensive crops; while that of climate change would be lower.

We can conclude nonetheless that implementing minimum environmental flows has costs—and these costs will be aggravated by climate change. We can also conclude that the costs from minimum environmental flows evolve in a non-linear fashion due to the adaptive strategies adopted by economic agents: initially, costs can be low even when water allocation reductions are significant; however, when water allocation reductions are sufficiently large, marginal incremental reductions can result in catastrophic economic losses as droughts test systems past the breaking point. Under these circumstances, it may be best for decision-makers to loosen up minimum environmental flow restrictions to mitigate disproportionate losses, in compliance with the law (OJ, 2000); although a more robust course of action would consist in anticipating these outcomes and design policies that align crop portfolios with common water management goals under uncertainty (Marchau et al., 2019), and thus prevent catastrophic failure. Options to achieve this include drought insurance, market reallocations or charges, among others. In fact, the interpretation that the European Commission makes of the WFD suggests that the costs (including financial, environmental and resource costs) of supplying water services should be recovered through charges, thus contributing to enhance economic efficiency. This interpretation nonetheless differs from the EU water *realpolitik*, where environmental objectives are pursued through programmes of measures where cost recovery ranges from insufficient (financial costs) to non-existent (environmental and resource costs). In a recent case (Case C-525/12, European Commission v. Germany), the European Court of Justice was called upon to clarify the scope of the pricing principle within the WFD, concluding that water charges “are not the central and definitive instrument for addressing the problems facing Europe in terms of water resources, but rather a specific measure which should be applied in connection with [other measures]” (Jääskinen, 2014).

Independently of the interpretation on what instrument should be used to articulate environmental flows, these are critical to achieve the objectives of the WFD, but also of other important international and EU directives and initiatives, including *inter alia* the World Heritage Convention (UNESCO, 1972), the Ramsar Convention on the Conservation of Wetlands (UNESCO, 1971), the European Commission’s Birds (OJ, 2009) and Habitats (OJ, 1992) directives, and the EU’s Biodiversity Strategy for 2030 (EC, 2020). The EU Biodiversity Strategy aims to conserve and restore ecosystems and contains specific actions and commitments towards this goal, including achieving the restoration of at least 25000 km of free-flowing rivers, that at least 10% of agricultural area is under high-diversity landscape features, and that at least 25% of agricultural land is under organic farming management. All the above should strongly affect agriculture and environmental flows management—albeit it should be noted that this environmental strategy

conflicts with other recent developments in the EU and national agricultural agendas. Most notably, the modernization of collective irrigation infrastructures such as canals is eligible to receive direct payments under the new Common Agricultural Policy (CAP) of up to 90% of the investment cost. This investment will be complemented with an additional EUR 700 million from the EU-funded Spanish Plan for Recovery, Transformation and Resilience, which aims to modernize 100000 ha in Spain under its third component (“Digital and environmental transformation of the fishing and agricultural sectors”) (Government of Spain, 2021). These investments, which are designed on the basis of a supposedly higher environmental performance, in reality will increase consumptive uses at the expense of reduced return flows—thus negatively affecting environmental flows and other economic uses downstream (Pérez-Blanco et al., 2020).

The methodology proposed in this paper and its application to the Douro River Basin offer novel contributions to (1) socio-hydrology research and to (2) water policy planning and decision-making:

- **Contribution to socio-hydrology research:** 1) We develop a set of two-way feedback protocols based on effective water use and water allocation variables to connect human responses occurring at a local level with their impacts on water systems at a basin scale, thus transcending the analysis of isolated actions of human agency at a local scale and assessing policy impacts at the relevant basin scale. 2) The hierarchical framework proposed in this paper offers a dynamic representation of the co-evolution of human-water systems, an improvement with respect to other recent static protocol-based modular contributions (Essenfelder et al., 2018). 3) The coupling is flexible and makes possible the use of other mathematical programming models in the economic model, such as Positive Mathematical Programming or Linear Programming models (Sapino et al., 2020). 4) The coupling is also replicable, i.e. other hydrologic models can be incorporated by revising and adapting the protocols. 5) The flexibility and replicability of the proposed hierarchical framework are instrumental towards the development of ensemble experiments that sample modeling uncertainty by incorporating multiple models at the level of each system.
- **Contribution to water policy planning and decision-making:** The coupled PMAMP-AQUATOOL model presented in this paper has been developed at the request of the Douro River Basin Authority and the Spanish Ministry for the Ecological Transition to address ongoing challenges in the design of minimum environmental flows and other water policies. In a first stage, the Douro River Basin Authority commissioned the authors the development of an actionable hydro-economic model that could be used to inform the design of minimum environmental flows, which were set to be revised throughout the basin as part of the 2021 Douro River Basin Management Plan (pilot stage of the research, 2018–2020). A specific demand from the Douro River Basin Authority was that the model should be based on the DSS AQUATOOL, the DSS used by the Douro and most Spanish river basin authorities. Subsequently, the research received complementary funding from the Spanish Ministry for the Ecological Transition to scale up the analysis and include water charging as well as two more basins (demonstrator stage of the research, 2019–2022), so that the proposed coupled model could be adapted and used to inform alternative policies elsewhere.

There are several ways in which future scientific research can improve and expand the hierarchical coupling of human-water systems proposed in this paper. Within the hydrologic module, a more detailed representation of the impacts of climate change on the water system is warranted. The climate change scenarios used by the Douro and other Spanish river basin authorities work at a sub-basin/catchment level, which can be readily downscaled using state-of-the-art climate models (Fischa et al., 2014). Additionally, policies other than quotas (e.g. charges) could be explored to achieve the water allocation targets set by

the hydrologic network optimization algorithm, albeit this is ultimately constrained by issues of technical (e.g. metering at a farm level) and institutional capacity (institutional lock-in, transaction costs) that deserve careful consideration. Within the microeconomic module, future models should incorporate the option for farmers to adapt at the intensive margin through deficit irrigation. This option is not included in conventional microeconomic models, which focus on extensive margin (land reallocations towards less water intensive crops) and super-extensive margin (land reallocations from irrigated to rainfed agriculture) adaptation. Including the option to modify soil use, e.g. through the decreased tillage or alternative crop rotations, would add further realism to the model. Future PMAMP models could also explore complementary attributes, albeit this is limited by data availability. Finally, both the hydrologic and the microeconomic module could benefit from the incorporation of alternative models/model settings to sample modeling uncertainty, leveraging on the flexible coupling developed in this paper. This multi-system, multi-model ensemble could be tested using alternative forcings, including charges, nature-based solutions, etc. or combinations thereof. The resultant grand ensemble would allow researchers and decision makers to better understand the cascading effects of uncertainty across coupled human-water systems, and to adopt better informed and more robust decisions.

Another improvement could be achieved through the addition of systems other than microeconomic and hydrologic, e.g. through the incorporation of an ecological or macroeconomic module. For example, the microeconomic model could be complemented with a macroeconomic model following recent contributions to the literature that explore the two-way feedback links in coupled micro-macro-economic systems (Parrado et al., 2020). Importantly, since the objective of our research is that of effectively mainstreaming advances in socio-hydrology and socio-ecology into decision-making, it is important that decision makers are continuously and effectively engaged in these developments, as was done in this paper, and to that end the scientific research and research outputs should be *actionable*. Therefore, researchers need to be aware and properly balance the tension between the hierarchy's ability to accurately represent the manifold relevant processes involved in complex human-water systems, and its ability to deliver inputs that can be readily used in decision-making. Arguably, by relating the behavior of complex socio-ecological systems to that of individual system models of decreasing complexity, hierarchical frameworks offer a more plausible, realistic and efficient approach to actionable interdisciplinary research. However, this approach is also limited by the bounded rationality of decision makers. Increasingly complex hierarchies that study a growing number of systems and variables to offer more detailed predictions risk becoming a sort of "black box" for decision makers, which cannot understand the processes that drive their outcomes. Thus, additional degrees of complexity can limit the ability of the decision-maker to derive heuristics of value, which can better inform future modeling efforts and are critical to decision making.

Finally, while this study represents an improvement in the spatial detail with respect to previous (micro-)economic studies that work at a coarser scale (agricultural districts, of which there are 55 in the Douro River Basin, as opposed to the 150 AWDUs used in this paper) (Parrado et al., 2020), future studies should look into alternative ways to increase granularity and move closer to the farm scale.

Credit author statement

C. Dionisio Pérez-Blanco: Conceptualization, Formal analysis, Funding acquisition, Investigation, Resources, Project administration, Methodology, Supervision, Writing - original draft; Writing - review & editing; **Laura Gil-García:** Data curation, Investigation, Software, Writing - review & editing; **Pablo Saiz-Santiago:** Methodology, Software, Validation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research leading to these results has been developed with the support of the Program for the Attraction of Scientific Talent's SWAN (Sustainable Watersheds: Emerging Economic Instruments for Water and Food Security) Project, and of the Ministerio para la Transición Ecológica y el Reto Demográfico, through Fundación Biodiversidad (ATACC Project - Adaptación Transformativa al Cambio Climático en el Regadío).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2021.113432>.

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