



Research

River basins as social-ecological systems: linking levels of societal and ecosystem water metabolism in a semiarid watershed

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ABSTRACT. River basin modeling under complexity requires analytical frameworks capable of dealing with the multiple scales and dimensions of environmental problems as well as uncertainty in the evolution of social systems. Conceptual and methodological developments can now be framed using the wide socio-eco-hydrological approach. We add hierarchy theory into the mix to discuss the conceptualization of river basins as complex, holarchic social-ecological systems. We operationalize the social-ecological systems water metabolism framework in a semiarid watershed in Spain, and add the governance dimension that shapes human-environment reciprocity. To this purpose, we integrate an eco-hydrological model with the societal metabolism accounting scheme for land use, human activity, and water use. We explore four types of interactions: between societal organization and water uses/demands, between ecosystem organization and their water requirements/supplies, between societal metabolism and aquatic ecosystem health, and between water demand and availability. Our results reveal a metabolic pattern of a high mountain rural system striving to face exodus and agricultural land abandonment with a multifunctional economy. Centuries of social-ecological evolution shaping waterscapes through traditional water management practices have influenced the eco-hydrological functioning of the basin, enabling adaptation to aridity. We found a marked spatial gradient on water supply, use pattern, and impact on water bodies from the head to the mouth of the basin. Management challenges posed by the European water regulatory framework as a new driver of social-ecological change are highlighted.

Key Words: *holarchy; river basin; socio-eco-hydrology; social-ecological systems; water availability; water metabolism*

INTRODUCTION

Water resources degradation is a complex environmental problem that involves multiple dimensions and scales of analysis. As the awareness over the human alteration of the global water system gained acceptance within the scientific community, the connections of local processes to global drivers and of human and environmental systems became key research objects (Vörösmarty et al. 2013). Watersheds have been the traditional observation system for hydrological studies focused on the reproducibility of water resources within the water cycle. Water basins are both a biophysical unit for hydrological modeling and a governance tool for water decision making in many countries (Cohen and Davison 2011, Del Moral and Do Ó 2014). As such, institutional performance and governance structures are drivers of change as much as biophysical and socioeconomic processes. Recent efforts of integrated river basin modeling strive to predict the effects of decision making on water allocation and land uses over the hydrological system under a range of scenarios (Jakeman and Letcher 2003, Henriques et al. 2008, Liu et al. 2008). Although these models are powerful in hydrological response forecasting, uncertainty in societal choice predictions is still a major challenge (Letcher et al. 2007). This is partially because of the local specificity of the complex organization of social systems as driver for environmental change, making extrapolation between contexts difficult. Nevertheless, water accounting methods, like virtual water (Allan 1998), water footprint (Hoekstra and Chapagain 2006), or social metabolism (Fischer-Kowalski 1998, Swyngedouw 2006) have engaged in trying to understand the socioeconomic and political drivers of water-use patterns, attempting to bridge scale mismatches with biophysical variables. Insights on the interactions between social, ecological, and

hydrological processes have been proposed within analytical frameworks of social-ecological systems (SES; Madrid et al. 2013).

Complexity theory deals with the epistemological implications of: (1) multiple scales and dimensions of analysis and (2) high stakes and uncertainty in decision making in coupled human-environmental systems (Liu et al. 2007). The representation and analysis of river basins as complex SES is still incipient, although some important works have been developed recently. Rathwell and Peterson 2012 addressed cross-scale interactions between water management and the provision of ecosystem services. Pahl-Wostl et al. (2010) proposed the management and transition framework for the analysis of water governance regimes, which they have later applied in at least 29 river basins all over the world (Pahl-Wostl et al. 2012). Mix et al. 2015 combined qualitative and quantitative methods to approach a diachronic analysis of multidimensional drivers of water-use change in an arid river basin. All these studies have two things in common: they depart from a networks approach to SES (Janssen et al. 2006), and they emphasize the role of policies and institutions shaping relations between social and ecological systems. However, none of them combine eco-hydrological modeling with socioeconomic quantitative analysis as integrated watershed modeling does, and none deal with the multiscale organization of SES.

Hierarchy theory is another branch of complexity approaching the analysis of SES (Pattee 1973, Allen and Starr 1988, Giampietro 2003). Networks theory and hierarchy theory are not exclusive but rather complementary analytical lenses, each having strengths and purposes (Allen and Giampietro 2014). Although network approaches to SES gain analytical dynamism by focusing

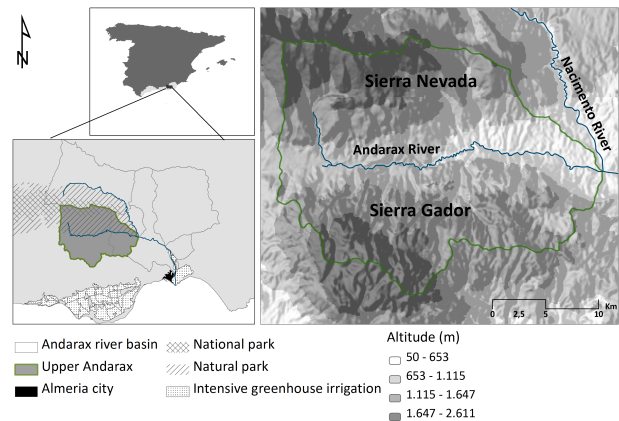
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on change with conceptual devices such as drivers, thresholds, and resilience, hierarchy theory is more robust on scaling issues and looking for principles of categorization of living systems organization by using concepts such as descriptive domain, surfaces, or holons. Madrid and Giampietro (2015) build on hierarchy theory to propose an analytical framework for complex SES based on the concept of water metabolism (SESWM). They strive to address the coexistence of multiple intertwined multilevel organizations of the different subsystems of a SES. According to the classification criteria for analytical frameworks of SES posed by Binder et al. (2013), the SESWM is an anthropocentric analysis-oriented framework that deals with the reciprocity among social and ecological systems by focusing on the feedbacks between their organization and their water exchange. Nonetheless, it does so through quantitative indicators without addressing the institutional layers of that reciprocity. We attempt to operationalize the SESWM framework to analyze the sustainability of water management in a semiarid Spanish watershed, the Upper Andarax. To this purpose, we integrate the eco-hydrological model BalanceMED (Willaarts et al. 2012) in the multiscale integrated analysis of societal and ecosystems metabolism (MuSIASEM) accounting scheme (Giampietro et al. 2009, 2011, 2014), and we add the governance dimension. We aim to look at the following questions: how does the socio-eco-hydrological functioning of the Upper Andarax Watershed work? What are the main drivers of socioeconomic change and their impacts over aquatic ecosystems? What are the water management challenges in the context of the current European water regulatory framework? What are the trade-offs associated with water management decisions?

STUDY AREA

The Upper Andarax Watershed is located in the southeastern part of the Iberian Peninsula in Almeria Province. According to the nomenclature of the European Union Water Framework Directive (EC 2000), it is part of the Andarax River basin, water exploitation system IV of the Andalusian Mediterranean River Basin District (Fig. 1). The Upper Andarax is a genuine catchment because of its uneven topography and its striking hydraulic heritage. The narrow valley runs between two great elevations, the Sierra Nevada foothills, to the north, and Sierra de Gador to the south. Land occupation in the Upper Andarax is extremely constrained by topography, with agriculture occupying 14% of the territory. Vegetation series correspond to *Quercus* spp. in the meso-mediterranean zone (until 1280 m) and *Juniperus* spp. in the supra-mediterranean zone (up to 2000 m), but representatives of these species are now very limited. *Pinus* spp. plantations are the most extended forest form usually mixed with shrubs. The major vegetation cover includes different types of xerophytic shrubs, well-adapted to the prevailing arid conditions. Predominant species are *Stipa tenacissima* (esparto), *Ulex parviflorus*, and *Festuca scariosa*. A system of traditional irrigation infrastructure (infiltration channels called “acequias,” flood collection “turbias,” and subsurface water collection “galerias”) and their local management communities have long ensured water availability in this dry environment (Pulido-Bosch and Sbih 1995). The social-ecological interest of the basin has driven a large amount of rich historical studies in the area (the Martínez and Usero 2010 book is a good compilation), yet there is less scientific literature on current socio-eco-hydrological functioning of the basin (Sánchez-Martos et al. 2013).

Fig. 1. Upper Andarax and its location within the Andarax River basin.



Human-environmental relations in the Upper Andarax are described from the Neolithic. We focus on the period when the international economic and political arena became key drivers for regional change. Contrary to other regions in Spain, Almeria had, from the onset of 19th century, an export-based economy thanks to its important harbor (Sánchez-Picón et al. 2011; Table 1). This first globalization brought a flourishing lead mining activity lasting over a century until its international depreciation. The depression was succeeded by a second mining boom, the iron time, as well as the cultivation of grapes, oranges, and esparto grass, which were in high demand in England through much of the 20th century. These activities drove major land-use changes, including a massive process of deforestation, which forced the development of an impressive system of agricultural terraces on the riverbanks to reduce the risk to floods (Latorre et al. 2001). Miners excavated cisterns, which collected subsurface water flow for agriculture, leading to the creation of important water user communities to manage the new resources. Much of the mountainous areas were also terraced and reforested with *Pinus* spp. during the reforestation campaigns of the Franco's dictatorship (Martínez et al. 2008). The second globalization begun at the end of 19th century and elicited the decline of this economy and the first emigration boom between 1980-2000 (Sánchez-Picón et al. 2011). Part of this boom followed an internal drift from upper mountain areas to the coast where the grape cultivation infrastructure was repurposed to introduce intensive vegetable production in plastic greenhouses for distribution in the European market (Mateo 2013).

The northern Sierra Nevada is one of the most important hotspots for plant diversity and endemism in the Western Mediterranean region and includes an impressive geomorphological system with more than 15 peaks over 3000 meters at 50 km from the sea. It was declared a biosphere reserve in 1986 by UNESCO and a natural park, aimed at integrating sustainable human activities within conservation goals, by the Andalusian government in 1989. The most ecologically valued area, i.e., the higher peaks covered by snow in winter, was declared a national park in 1999, phasing out traditional human activities like agriculture, hunting, and gathering within its boundaries.

Table 1. Drivers of social-ecological change.

International driver	Regional driver	Period	Social-ecological changes
First globalization	Mining	End of 18th - end of 19th	Deforestation, floods, cisterns excavation
Economic crisis	Grape production	End of 19th - end of 20th	Terrace system
Second globalization	Reforestation	1939-1975	Pine plantations extension
	Emergence of greenhouse production in coastal area	1980-2000	Rural exodus, agricultural land abandonment
United Nations Program Man and the Biosphere	Sierra Nevada protection	1986-1999	Land uses regulation
Water Framework Directive	Environmental objectives achievement	2010-2027	Good ecological status of water bodies
Common Agricultural Policy	Competitiveness within international markets	2008-2014	Agricultural intensification

The basin currently consists of an aged population of 8873 inhabitants distributed in 14 municipalities (INE 2011). However, the pictorial agricultural landscape is an identity element being gradually abandoned as agricultural productivity decreases. The main occupations in the upper municipalities closer to the national park are related to ecotourism, turning to agriculture in the central part until the last municipalities at the mouth of the basin, which are mainly working in the services sector.

Current challenges posed by European water and agricultural policies derive from their planning objectives, which are usually conflicted (Cabello Villarejo and Madrid López 2014). The European water governance strategy was set with the Water Framework Directive in the year 2000. As exemplary implementation of the integrated water resources management paradigm, each river basin in Europe had to establish a new adaptive management regime in planning cycles of six years. The overall objective is the recovery of “good ecological status” of all water bodies in Europe by 2015. The first river basin management plan for the Mediterranean Andalusian River Basin District was released in 2010. The plan assessed, for the first time, the ecological status of surface and groundwater bodies in the region and established environmental recovery objectives for the time horizons of 2015 and 2027.

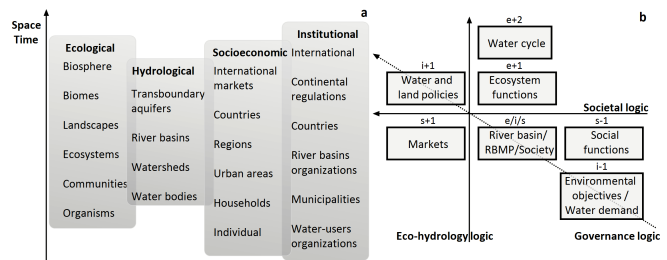
METHODS

River basins as complex holarchic social-ecological systems

River basins have been represented using different analytical lenses: hydrological, ecological, institutional, or socioeconomic (Fig. 2a). Each analytical dimension is a criterion for observation and can itself be approached as a hierarchy with multiple nested levels. Hierarchies have been described for ecosystems (Allen and Hoekstra 1992, Jørgensen and Nielsen 2013), hydrological systems (MacLachlan and Moulton 2006, Li and Ren 2010), institutions (Gupta and Pahl-Wostl 2013), agro-ecosystems (Giampietro 2003, Ewert et al. 2011), and social systems (Scholz and Binder 2003, Giampietro et al. 2014). All of these criteria are relevant when conceptualizing the river basin as a social-ecological system. The dual fuzzy identity of levels in a hierarchy, which are at the same time parts and wholes, structural compartments (a water mass) and functional types (a typology of water bodies), is captured by the concept of holon (Koestler 1972, Serrano-Tovar and Giampietro 2014). Feedback loops

occur within holons and across levels and dimensions. The problem is how to operationalize the existence of these coexisting holons in a common frame of analysis and deal with the transfer of information between descriptive domains. In research practice, this has been tackled through the institutional analysis of environmental governance regimes in some of the most popular frameworks for SES analysis (Scholz and Binder 2003, Ostrom 2009, Pahl-Wostl et al. 2010).

Fig. 2. (a) Descriptive domains for a river basin. Adapted from Ewert et al. (2011); (b) Multiaxes holarchy for a river basin as a social-ecological system (SES). Adapted from Madrid and Giampietro (2015).

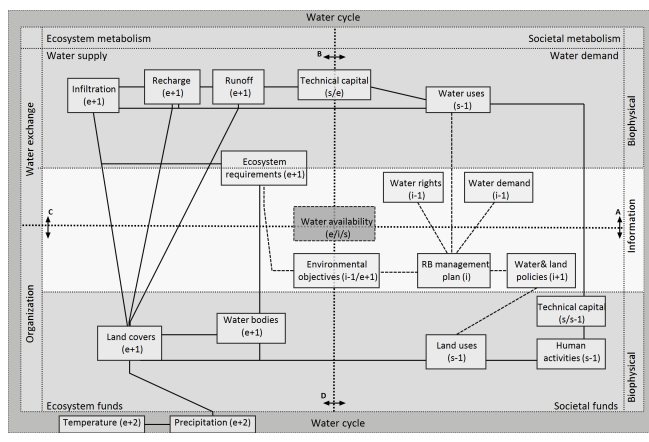


Madrid and Giampietro (2015) propose the combination of the two classical descriptive domains in hydrological studies: the “watershed” (eco-hydrology logic, “e”) and the “problemshed” (societal logic, “s”) in a holarchic basis (Fig. 2b). Any holon is composed of a physical part that exchanges biophysical flows to reproduce itself and a coded part that handles its information (Allen and Giampietro 2014). We add a transversal axis representing the “infoshed” (governance logic, “i”) produced at different levels that shape societal metabolic patterns and interaction with their contextual environment. Our focal level (e/i/s) is the physical river basin and its society, linked through the river basin management plan (RBMP), which establishes water allocations. Upper and lower levels in the axes establish the external and internal constraints to the self-organization of the socio-ecosystem.

We structure the multiaxes into the general analytical framework (Fig. 3) arranging analytical categories in four quadrants: ecosystem/societal metabolism and water exchange/organization.

Hydrological processes in a watershed sustain a wide range of ecosystem services. A great part of the rainfall within a basin is stored in the soils and evapotranspired by plants, providing services like microclimate regulation, rain-fed agriculture, or forest products. Another share of the annual rainfall flows into aquatic ecosystems and is often regulated to ensure human water supply through the development of infrastructures (technical capital). Water, land, and other environmental policies affect how much water is stored in soils and water bodies by normatively setting environmental objectives, aquatic ecosystem requirements, land-use changes, and new infrastructure developments. These policies are usually produced at higher governance levels than the basin itself, framing the strategies for river-basin management, which then have to encounter local realities. We represent four interfaces in which we can address different types of interactions between (1) the organization of social systems and water use/demand (A), (2) water demand and water availability (B), (3) the organization of ecosystems and water supply (C), and (4) the organization of societal metabolism and ecosystem health (D).

Fig. 3. Social-ecological system based on the concept of water metabolism (SESWM) analytical framework adapted from Madrid and Giampietro (2015) to the Upper Andarax basin.



Water availability

Water availability is a concept approached from multiple definitions and perspectives (Table 2). The most common one refers to the long-term average freshwater volume yearly supplied by the hydrological cycle, including runoff and aquifer recharge (see for instance Menzel and Matovelle 2010, Parish et al. 2012, Post et al. 2012). In this sense, it equates to the Falkenmark and Rockström (2004) concept of blue water. Other approaches encompass the environmental flows (e-flows) as a prior allocation to what is available for humans (Poff et al. 2010, Hoekstra et al. 2012) or focus on the reproducibility of specific end uses (Henriques et al. 2008, Molden et al. 2011, Padowski and Jawitz 2012).

Availability, in a social-ecological sense, is a dynamic boundary concept between societal water uses, expectations on additional water requirements (demand), technical capital to regulate water bodies, and desired ecosystem integrity. Defining availability is the process of determining what is considered a resource for a specific, usually human end use, and what is not. For instance, on

defined aquifers water “becomes available” when technological advances and energy prices allow deeper pumping, as long as there are no adverse effects that the social system using the groundwater is not willing to accept (del Moral 2005:16, Zhou 2009). As a normative category, water availability depends on which are the accepted trade-offs between water extraction and environmental, economic, and social consequences of this extraction. Because narratives on availability might differ depending on whom you ask, especially when water allocation implies uncertainties and high stakes, a normative definition of availability is usually set as a compromise to avoid conflicts, or as an imposition of a party, in the frequent case of existence of unbalanced power relations. Despite formal commitments or authoritarian impositions, the implementation of the resulting standards are often subjected to infringements, a not incidental but structural atmosphere of deviance or noncompliance with legal norms. This is the case of the region in which the Andarax is located (Sampedro and Del Moral 2014). Nonetheless, what is allocated as available at one scale for an end use will entail trade-offs, and thus, create winners and losers. Therefore, further negotiation with those affected is usually required. For instance e-flows established in European river basins are calculated first and negotiated afterwards (see for instance section 4.3.6 of the Spanish water legislation http://www.magrama.gob.es/es/agua/legislacion/iph_tcm7-207591.pdf).

Table 2. Water availability definitions for different systems.

System	Water availability	Trade-offs
Whole social-ecological system	Total water inflow to the river basin including precipitation (minus evapotranspiration), inflow from other aquifers, and from external transfers	With other river basins
Land subsystem	Soil water that can be used for plant transpiration	Between productive and nonproductive uses
Aquatic subsystem	Ecosystem requirements of surface and groundwater (normatively established)	With societal appropriation
Human subsystem	Total water available for human direct appropriation from different sources	Between human demand and impact on ecosystems
End users	Water that can be used by each end user according to institutional regulation	Between end users

When moving from semantic to formal categories of water metabolism analysis, we need to make explicit the definition of water availability being considered. This definition is at the core of any water use sustainability assessment and introduces a value judgment into the scientific analysis, a preanalytical decision made by the analyst. Molle and Mollinga (2003) defined water scarcity in terms of scarcity of what and for what. When using normative concepts such as sustainability, scarcity, or availability, these questions become relevant: availability of which type of resource, for what type of end use, at what costs, and for whom. In the interface of society and ecosystem, the definition of available water (Box 1) deals with the trade-offs between allocation of water for productive uses or ecosystem conservation.

Box 1: Water availability at the ecosystems/society interface.

Water availability for society = Σ (surface + groundwater + produced + transferred + soil) available water

Surface available water = Compromised diversion from the river and reservoirs within established environmental flow regime for aquatic ecosystems

Groundwater available water = Compromised pumping rate within an established sustainable yield

Reclaimed available water = Wastewater reuse + desalination capacity

Transferred available water = Transfers from other basins

Soil available water = Soil moisture appropriated for human use for plant growth and food production

The water grammar in multiscale integrated analysis of societal and ecosystem metabolism (MuSIASEM)

Our methodological purpose is the operationalization of SESWM to link the analysis of societal metabolism to variables of ecosystem metabolism that are relevant for river basin management. Our lenses are on the social scale of observation: we do not study the functioning of ecosystems themselves but the interactions between ecosystems and society as a consequence of societal organization. Therefore, as an ecosystem water metabolism analysis, we focus on the eco-hydrological processes that control water resource renewability (supply side), the impacts caused to ecosystem health (sink side), and the boundary concepts of water availability and ecosystem water requirements. To this purpose, water metabolism is quantified through the water grammar, tying the semantic representation of the system metabolism (Fig. 3) to the holarchic organization considered (Fig. 2b).

A grammar is a formal system of rules for accounting metabolic flows, given a set of expected relationships between semantic categories of what we want to indicate (for instance sustainability) and formal categories (indicators, data, and rules for calculation). The MuSIASEM uses different interrelated grammars for the water, energy, land, and food nexus (see Giampietro et al. 2014), based on the flow-fund model of Georgescu-Roegen (1971). Fund variables are those remaining the same over the time duration of the representation (or those that we want to conserve) whereas flows are those that are consumed or produced to maintain and reproduce funds. Common societal funds used in MuSIASEM are human activity (measured in hours), technical capital, and land. Land is, at the same time, an ecological and societal fund. The specificity of water as a resource is important in that it changes its semantic definition from a fund in ecosystems (long-term patterns of water cycle change) to a flow in most societal uses (managed through year planning). Note that, although most approaches consider water bodies as stocks (see for instance Falkenmark and Rockström 2004), the difference between stocks and funds is essential in the metabolism approach (Giampietro and Lomas 2014). Stocks are nonrenewable resources at the time scale of the representation, like reservoirs or aquifer overdraft, which consumptive use diminishes availability for ecosystems or

for future needs. Funds are resources consumed at a slower pace than their renewability rate during the representation, like aquifer sustainable yield or soil moisture. Ecosystems live on water fund limits. Water flows for human use can come from a stock or a fund because we can create artificial stocks to increase available water flows or overdraft funds from remaining stocks (fossil waters).

The water grammar provides a set of useful semantic categories for multilevel accounting of ecosystems ($e \pm i$) and societal ($s \pm i$) water metabolism (Madrid and Giampietro 2014; Table 3). Flows and funds are classified in typologies explicitly tailored to each case study according to criteria defined at each level of observation. Water flows are typologies associated with provisioning ecosystem services that change water characteristics in its use. Water funds sustain ecosystem functions that supply all types of services. There are also human uses of water funds, like navigation or electrical generation, which are not relevant to this case study. Water funds are required all at once whereas flows are required at a specific pace. In addition, they are all required to have a specific set of useful attributes, i.e., quantity, quality, timing, and location (Brauman et al. 2007).

The grammar is quantified through extensive variables (total flows and funds), and relational indicators (flow/flow, flow/fund) are summarized in Table 4. As shown in Figure 3, we consider four types of interactions between ecosystems and society. Relation A describes the intensity of water use required to maintain a human activity or land use. Relation B describes the degree of exploitation of water funds (supply side) for direct human uses. Relations type C are two-sided: on one hand, the generation of water funds (runoff, recharge, soil infiltration) per type of land cover; on the other, the ecosystem water requirements mediated by normative societal decisions on availability and land uses. The feedback D, environmental loading, refers to the impact of the societal metabolism over aquatic ecosystem health (sink side).

Modeling

To build up this grammar into formal categories several models/tools have been integrated:

- Climate: a series of monthly median precipitation and mean temperature measurements for the period 1970/1971-2000/2001 from 24 meteorological stations have been interpolated through inverse distance weighting (IDW) in ArcGIS 10.2 and used for potential evapotranspiration calculation with a Thornthwaite based Microsoft Excel macro.
- Eco-hydrology: the BalanceMED model (Willaarts et al. 2012) is a semideterministic model able to quantify the mean hydrological functioning (i.e., partition of annual precipitation into runoff, aquifer recharge, and soil moisture) of Mediterranean basins using long time series of mean monthly rainfall and potential evapotranspiration. Because BalanceMED is a spatially explicit model, the Upper Andarax was divided into so-called hydrological units (HU), which are unique combinations of Land Use Land Cover (LULC) and soil types. Such divisions allow the identification of potential differences in the eco-hydrological functioning across the basin. The model uses the APLIS equation (Andreo et al. 2004) to assess the soil percolation capacity (i.e., potential aquifer recharge).

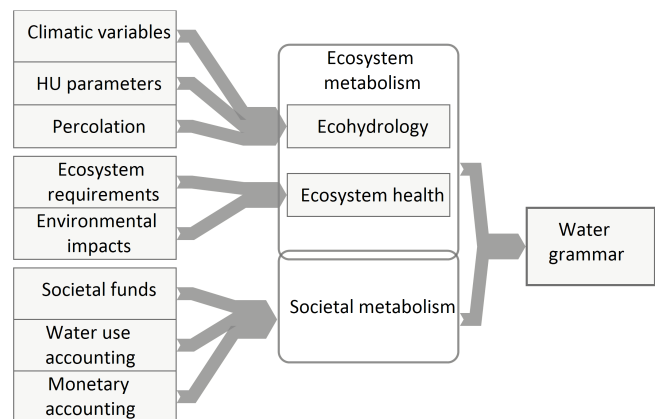
Table 3. Water grammar for the Upper Andarax basin. Adapted from Madrid and Giampietro (2014).

System definition	Water Exchange			Organization		
	Role	Semantic categories	Types	Role	Semantic categories	Types
Water cycle e+2	Fund	Climate	Precipitation	Fund	Climate	Potential Evapotranspiration
Ecosystem functions e+1		Water funds turnover	Runoff Recharge Infiltration		Land covers	<i>Quercus</i> and riparian forests Plantations Shrubs Pastures Irrigated agric. Rain-fed agric. Abandoned agric. Rivers Aquifers
Water funds Focal level e		Available water for societal appropriation	Surface Groundwater Soil moisture		Water bodies	
Society Focal level s	Flow	Gross water use	Withdrawn Soil	Fund	Human activity	Physiological overhead Social, Leisure, and Education Unpaid work Paid work
Societal functions s-1		Net water use	Urban supply Food production Forestry Esparto gathering Cattle		Managed land uses	Plantations Shrubs Pastures Irrigated agric. Rain-fed agric.
i-1		Demand	Withdrawals		Technical capital	Transport infrastructures Irrigation technology
				Flow	Money	Agricultural costs Gross added value water costs Municipal gross rent

Table 4. Relational indicators.

Relation	Indicator	Description
A	Water metabolic rate	Gross water use per hour of human activity
B	Water extraction index	Surface water: ratio of water withdrawals out of total runoff, e-flows discounted Groundwater: ratio of water abstraction out of total recharge, discharges to springs discounted
C	Environmental impacts	Surface and groundwater quality Water table level changes Erosion rates
D	Ecosystems water requirements	Soil: transpiration River: e-flows Groundwater: discharge to springs

Fig. 4. Process overview.



- Societal metabolism accounting: this includes water and monetary flows and land, human activity, and technical capital funds. We use the pie chart representation for rural-systems analysis adapted from the Serrano-Tovar and Giampietro (2014) template. It includes their interactions with three types of contexts, i.e., urban system, external markets, and water funds. Associated land-cover uses and green water flows were estimated with a fuzzy approach of shares-use coefficients per type of cover (see Appendix 1).

- Environmental impacts: annual rates for erosion and water table level changes have been averaged for available series between 1992 and 2006. Water-quality measurements in existing control points in the watershed were averaged for available series between 2002 and 2013.

The process consisted of spatial processing of the physical variables in ArcGIS 10.2 to feed the eco-hydrological model on one side, and on secondary data processing to feed the societal metabolism accounting on the other (Fig. 4). Both were

conducted in R, and results were gathered in ArcGIS geodatabases. Results, analysis, and discussion were completed through two months of fieldwork observations and nine semistructured interviews of key informants in the basin (March-April 2014). For a detailed methodological description on data sources, model calibration, variables calculation, and links to databases and codes please refer to the methodology in Appendix 1. Note that the levels specified in the grammar follow an organizational scale of observation, i.e., holons in a social-ecological system. Formal categories of the grammar and the spatial and temporal scales used for modeling are given in Table 1 and Figure 1 of the Appendix.

How do we calculate water availability?

As Del Moral (2005) and Zhou (2009) illustrated, water availability is almost impossible to calculate on a general basis because of its strong dependency on normative frameworks, technical capital, and accepted trade-offs of water withdrawal. The Spanish water management legislation only defines water availability for groundwater as “the average year-to-year value of total recharge of the water body minus the average year-to-year flow required to achieve environmental objectives, to prevent any further significant deterioration of the ecological status and significant damage of dependent terrestrial ecosystems” (MARM 2008). This complex definition is not complemented by a harmonized framework for its assessment, especially with regard to the connection of ground to surface water bodies, leaving the definition of “significant” damage open to interpretation. As a result, aquifers are usually treated as black boxes in the RBMPs, and the lack of spatially explicit aquifer modeling hinders their governance robustness (De Stefano et al. 2014). We calculate the year availability for societal appropriation based on available data as:

$$WA_{Surface} = DSF - EF \quad (1)$$

$$WA_{Ground} = RE + IRF + IIR + IF - OF - EF$$

Where *DSF* are water diversions from the river, *EF* are the e-flows, *RE* is the annual recharge from rain, *IRF* the infiltration from runoff, *IIR* the infiltration from irrigation returns, *IF* the lateral inflow, and *OF* the lateral outflows to other aquifers. We assumed the regime of surface e-flows estimated in the RBMP as well as the average annual estimated discharge to the 58 natural springs as a proxy for groundwater ecosystem dependency.

Modeling limitations

The most important drawback of our study is the unavailability of a temporal series of water-use data hampering a diachronic analysis. In addition, the wide and diverse secondary data requirements for the social metabolism analysis forces the integration of data measured in different periods. For this reason, we can only get a snapshot of the average water metabolism in the region between 2000 and 2008. This is the same timeframe as the baseline measurements produced for the RBMP released in 2010. Regarding the eco-hydrological model, the surface-groundwater interactions and the influence of the snow on the hydrological regime are not considered. In addition, one of the main limitations is the difficulty to model the pronounced human alteration of the basin hydrology. We only consider human

terracing with regard to its effect on slope reduction but their explicit relation to erosion rates is not covered within our model. We decided to calibrate on a monthly average resolution because it is sufficient for our descriptive purposes given the constraints on social data.

RESULTS

Water funds (e+2/e+1)

The Upper Andarax climate is representative of Mediterranean areas: high evapotranspiration and marked seasonal and interannual irregularity of precipitation. Nonetheless, the high elevations of both sides of the basin and its orientation shape a harsh gradient in the spatial distribution of precipitation and potential evapotranspiration (Figs. 5a, b). The Northwest, mountainous Sierra Nevada presents a subhumid 630 mm of annual precipitation and temperature of 11 °C. The lower, southeastern area is classified as semiarid with a range 200-300 mm of annual precipitation, mean temperatures of 16 °C, and potential evapotranspiration of up to 890 mm. The presence of arid zones, characterized by the alternation of extreme events (drought and torrential rainfall), is usually a more determining factor than the small fluctuations in the mean values of the climatological variables. This irregularity is revealed by annual Pearson's coefficients of variation around 42%, increasing to over 200% for the driest months.

Water bodies are classified in typologies in the RBMP. There are two surface water bodies: the Alto Andarax, which runs from the spring until the first urban area, and the Medio Andarax, which continues then flowing down until the outlet. The two main groundwater bodies extend far beyond the watershed to coastal areas in which major exploitation takes place. Gador Sierra is a huge karst aquifer composed of permeable and fractured limestone and dolomites. As observed in Figure 5c, the recharge model shows a recharge capacity of over 80% for this area whereas siliceous Sierra Nevada has low permeability, and the detritus aquifer of Low Andarax medium (70-80%). Total mean annual precipitation for the modeled period was 138.2 Hm³, of which 76.6 turns into soil moisture, 36.4 percolates for aquifer recharge, and 15.7 flows as runoff. Figures 5d-f show the spatial distribution of these water funds. The influence of the precipitation pattern is clear in that 80% of runoff generation is concentrated in the northeast corner whereas most of the recharge is distributed all along the eastern strip. Middle and lower parts of the basin show lower runoff and recharge generation but still hold an important fraction of the soil moisture.

The average eco-hydrological indicators (Relations C) per land-cover type are presented in Figure 6. Transpiration, as the share of soil water invested in biomass productivity, is shown along with the annual rate of water evaporation, i.e., nonproductive fraction of soil water. Although representative of a small fraction of the territory, *Quercus* spp. forests and its combination with other types of vegetation (shrubs or pastures) and riparian forests transpire the largest fraction of soil moisture, followed by *Pinus* spp. plantations. As expected, more densely vegetated areas are more efficient in terms of water used to produce a unit of biomass because they have less water losses from soil water evaporation. The ratio of transpiration out of total evapotranspiration decreases in lower covers, such as shrubs and pastures. The effect

Fig. 5. Spatial distribution of (a) median annual precipitation; (b) potential evapotranspiration; (c) recharge capacity; (d) soil infiltration; (e) runoff; (f) recharge.

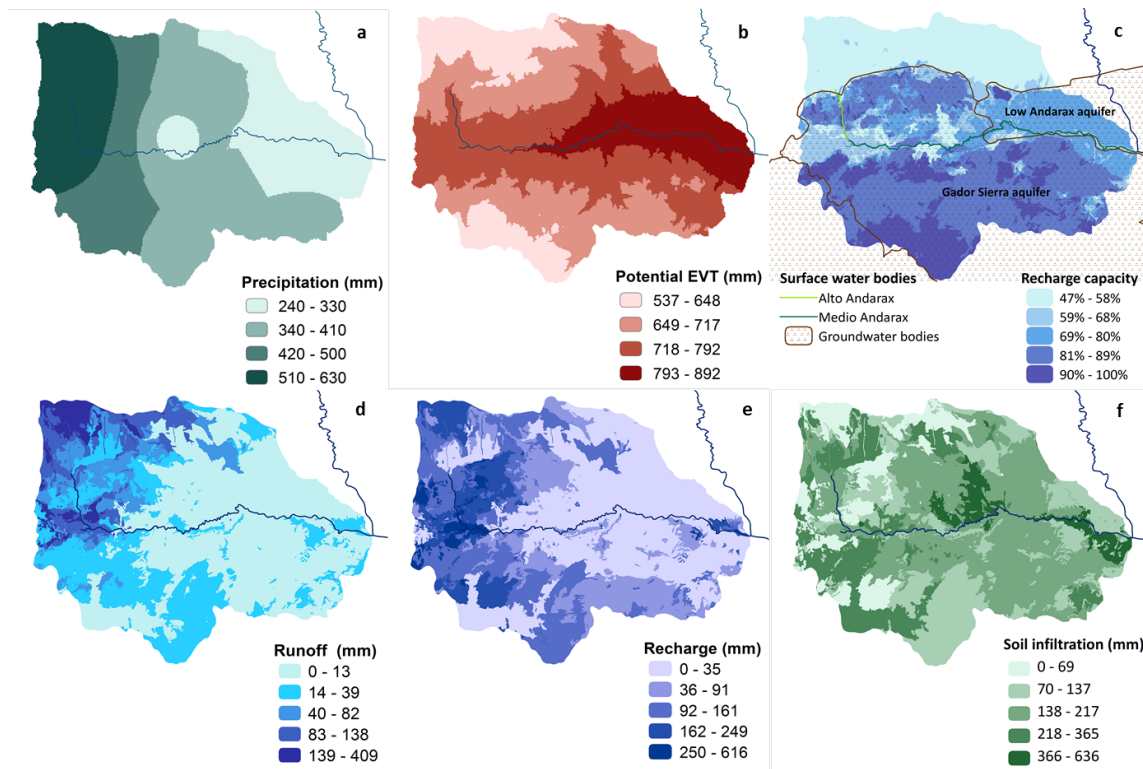
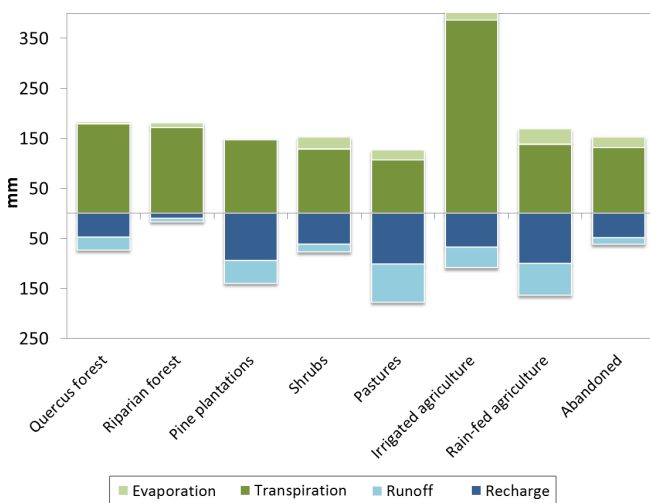


Fig. 6. Land ecosystem requirements and surface and groundwater recharge density per land use land cover (LULC) type (mm).



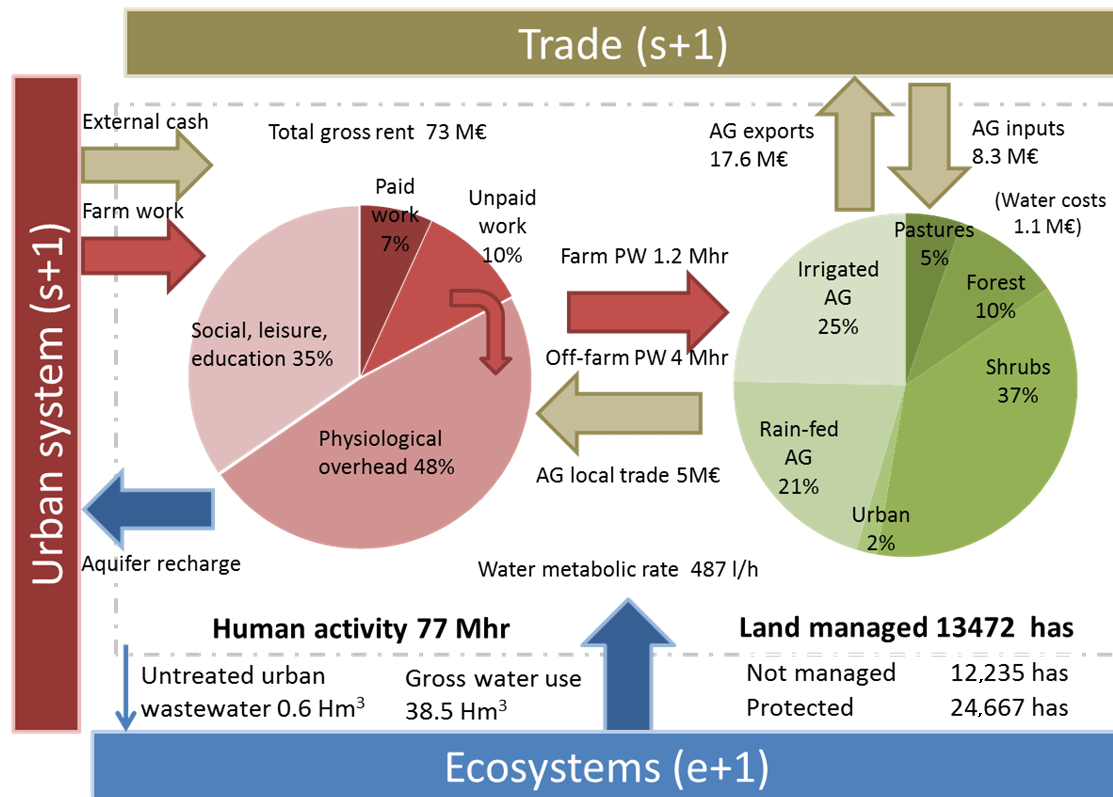
of terracing in agriculture can be detected in the rather high productivity of rain-fed agriculture as compared to similar cover vegetation like shrubs and pastures. Abandoned agricultural areas are substituted by shrubs showing a similar productivity.

Indeed, the analysis of variances showed significant differences in transpiration rates between all typologies ($p < 0.05$) except between plantations and rain-fed agriculture (both terraced), and between abandoned agricultural area shrubs and pastures. Irrigation significantly intensifies plant productivity in comparison with all other land uses. Recharge and runoff rates in this watershed are not so much determined by the land cover as they are by the geology, slope and spatial distribution of precipitation. For this reason, there are no clear statistical clusters based on LULC typologies. However, we found a significantly lower recharge rate on *Quercus* spp. forest compared to *Pinus* spp. plantations in both sierras, but no statistical difference with shrubs or pastures. Abandoned agricultural areas do not show statistical differences on their recharge rate with any other land-cover type whereas both irrigation and rain-fed agriculture areas have significantly higher average recharge rates than *Quercus* spp. forest and shrubs.

Societal metabolism (s/s-1)

Figure 7 shows a representation of societal metabolism of the whole Upper Andarax. The human activity budget shows a low share of hours devoted to paid work activities (7%), which have to sustain the monetary requirements for the rest of the hours (93%). A relevant point is that unpaid work, 7 million hours, in households is higher than paid work hours, with 88% of these hours sustained by women (gender disaggregation of human activity can be found in Appendix 1). Main working activities are the services and government sectors (50%), building (18%), and mining and industrial activities (9%). All of these occupy only 2%

Fig. 7. Annual societal funds and interactions with main contexts. AG: agriculture; PW: paid work; M: millions; Mhr: million hours.



of the total land used (urban areas), whereas most of human land uses are agriculture and other extensive land-cover exploitations (grazing, forestry, and esparto gathering) accounting for 23% of formal working hours.

About 77% of the watershed's agricultural production is traded in external markets, whereas the internal market sustains 33% of revenues obtained from agricultural products. The total municipal gross rent in 2006 was 73 million Euros, indicating an important contribution of agriculture to the local economy. Water costs represent 13% of agriculture expenditures and are very low for surface water (between 1-3 cents €/m³), and more fluctuating for groundwater (between 6-18 cents €/m³). The consequence of the emigration flow from the basin villages to downstream urban areas is an increasing input of working/leisure hours on weekends and the inflow of cash generated there.

The region contains a diverse pattern of rain-fed and irrigated crops, with a predominance of almond trees typically found in mountain regions in Spain because of their high adaptability to extreme conditions, i.e., poor soils, low soil moisture, and cold winters. Table 5 presents the economic and technical indicators of the different crops. As observed, irrigation substantially increases monetary productivity. The highest economic labor productivity (gross €/hour) is shown by almond production, because it is low labor intensive, followed by horticulture because of high market prices. Water transport systems are primarily

"acequias" and surface flooding represents the main irrigation technique. Only citrus production at the basin outlet has introduced drip irrigation.

Table 5. Irrigated and rain-fed crops. LU = land use.

	LU (has)	Gross €/ha	Gross €/hr	Use of acequias	Drip irrigation
Irrigated					
Almonds	1100	6708	20.0	56%	32%
Olive	847	4275	9.9	84%	15%
Horticulture	661	7333	14.2	98%	1%
Citrus	634	4773	9.1	62%	50%
Rain-fed					
Almonds	1092	1699			
Olive	333	1549			
Extensive	326	176			
Vineyards	312	2504			

The ecosystems-society interface (e/i/s)

Water exchange (e → s)

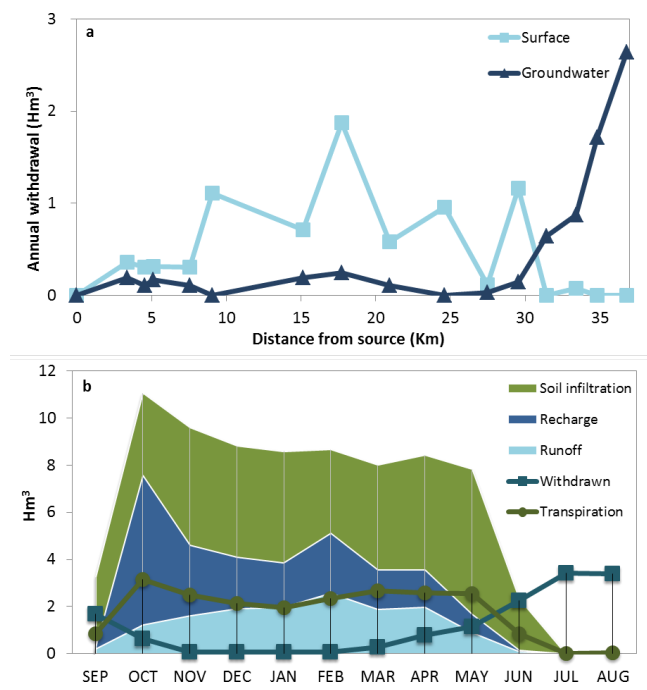
Table 6 shows the water flows sustaining provisioning services in the watershed. Soil moisture use is 50% higher than water withdrawals and sustains a greater variety of extensive land uses and associated services. Because there are no major industries or

big urban areas in the region, most of the water is used for food production. Cattle grazing also accounts for important soil water yields. Regarding the location of water withdrawals, most of the basin relies on surface water, with a special increment in the middle area for irrigation, whereas groundwater pumping concentrates in the last seven kilometers over the Low Andarax aquifer for citrus production (Fig. 8a). This change is caused by the drying out of the river whose main inflow at this point comes from urban wastewater discharges. When considering the seasonal variability (Fig. 8b), autumn and spring months are the rainiest acquiring most of the water inflow. In October, soil and aquifers refill after the summer and vegetation reaches its maximum transpiration. As observed, transpiration is almost coupled to infiltration whereas most withdrawals take place during summer to compensate soil moisture drought.

Table 6. Annual water uses in the Upper Andarax (Hm³).

		Withdrawn	Soil
s	Gross water use	14.2	21.6
	Losses	3.7	3.4
s-1			
Net uses			
	Urban supply	0.7	-
	Food production	8.8	8.2
	Forestry	-	1.9
	Esparto gathering	-	2.1
	Cattle	0.5	5.8

Fig. 8. (a) Spatial distribution of water withdrawals; (b) Seasonal distribution of water funds and flows.



Ecosystem health (s → e)

The river ecological status assessment in the RBMP considers the Alto Andarax in good status and the remaining section (Medio Andarax) in poor status. The main drivers of this poor status are the drying out of the river during the summer months because of diversion for agriculture, untreated wastewater discharge, and sediment deposition from erosion. Groundwater bodies are assessed as quantitatively and qualitatively poor status.

Figure 9 shows a clear spatial gradient on the impacts in the basin. In Alto Andarax, within the natural park, human activities are very constrained, and surface and groundwater quality meets drinkable standards (Fig. 9a). In the middle section (from km 10-25), main irrigation areas are located and nitrate concentrations in water increase, yet it falls within the good state category according to EUWFD reference of 6.5-9.5 mg/L (quality guidelines are gathered in Glavan et al. 2013a). Along the last 10 km of the Andarax River, fecal coliform concentrations are very high (up to 14,000 CFU/100 mL proper of untreated wastewater) and suspended solids reach 87 mg/L (EU Directive 2006/44/EC guidance level for surface waters of ≤ 25 mg/L), making water unusable for urban and agricultural purposes. According to the Andalusian scale for regional erosion, the average annual rate of soil loss between 1992 and 2006 is deemed low (12 tn/ha yr) in 65% of the basin, moderate in 27% (12-50 tn/ha yr) and high in 9% (> 50 tn/ha yr). Highest erosion rates are found from the middle section of the basin toward the outlet, clearly overlapping marls and conglomerates areas were most agricultural and abandoned agricultural areas are located (Fig. 9c). These rates align with other studies in the region in areas with abandoned terraces (Romero and Belmonte 2008, 2009). However, they are extremely severe compared to the threshold of 1 ton/ha recommended in other parts of Europe (Verheijen et al. 2009, Glavan et al. 2013a).

Fig. 9. (a) Average annual water table change; (b) Average annual soil loss rates (c) Average groundwater water quality; (d) Average surface quality.

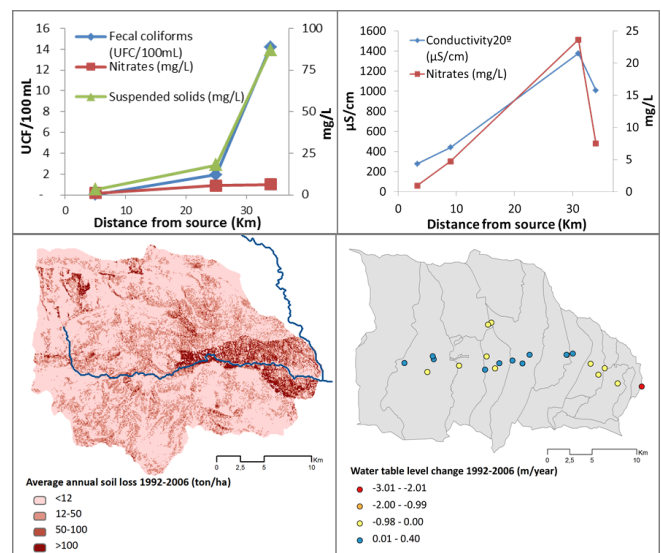


Table 7. Water demand vs availability (Hm³).

	Withdrawals	Ecosystems requirements	Water extraction Index (%)		Water availability average year	Water demand
			Average year	Dry year		
River	5.8	2	0.46	0.67	3.8	17.6
Aquifer	7.2	10	0.34	0.50	13.2	

Regarding groundwater (Fig. 9b), the Low Andarax aquifer clearly shows a higher conductivity and nitrate concentrations compared to the upper North Gador Sierra. This salinity has been related to the marl composition of the aquifer bed (Sánchez-Martos et al. 2005) and does not surpass the reference threshold for this type of water body in the EUWFD (3610 µS/cm). The nitrate peak indicates an influence of agricultural diffusive pollution even lower than the 50 mg/L threshold for groundwater poor state. Finally, water table level variations between 1992 and 2006 spatially overlap with groundwater withdrawals, decreasing in pumping areas (primarily concentrated on the Low Andarax aquifer) and increasing where the river is the major water source (Fig. 9d).

Water management (elils)

In line with the ecological status assessment, both groundwater bodies have been declared as subjected to “less rigorous environmental objectives” within the RBMP, because of the complex overdraft situation created by downstream intensive greenhouse farmers. This means that they need a longer recovery horizon (beyond 2015), conditioned to the generation of additional resources through desalination in the coast. There are no aquifer restoration measures foreseen for the Upper Andarax area but new dwells are forbidden along the whole water body until regularization of existing water rights is accomplished. On the other hand, the river horizon for “good status” retrieval was set for 2015. This poses a new external constraint to the societal metabolism: impacts have to be remediated and the e-flows regime implemented on the river.

The current annual water extraction index (WEI) for the average water funds in the modeled period shows that surface water bodies are more exploited than groundwater (Table 7). When considering a drought subperiod (1976-1988), we obtain a 17% reduction of renewable resources and a considerable increase of the annual WEI if the same water use is to be maintained. In addition, water demand is 37% higher than current water use because additional resources are claimed for irrigation. This demand can be met with available resources by substituting surface withdrawal for additional pumping, but this multiplies water costs by a factor of six. The proposed e-flows regime barely reaches 10% of runoff from October to March, but in summer months would require almost no diversion. Middle basin users who rely on surface water are those mainly affected by the e-flows implementation. The situation is totally stagnant because of the banning over new dwells and the lack of negotiation process with local irrigation communities on the proposed e-flows. This area counts the highest rates of agricultural employment and its rent per capita is low (4500-8000 € p.c.) compared to upper and downstream municipalities (8000-10,000 € p.c.). Therefore, turning to

groundwater or to rain-fed crops has an economic impact that needs to be further evaluated. The foreseen strategy in the RBMP to solve this conundrum is to not implement the e-flows regime until new available water resources are generated through irrigation-efficiency improvement by replacing the galleries and acequias by drip systems.

DISCUSSION

Several authors have described the alteration of the Upper Andarax hydrology through centuries of human transformations of the territory (Latorre et al 2001, Sánchez-Picón et al. 2011). Our results support these works by quantifying the increment of water availability for human productive uses, especially of soil water. Despite the importance of local wisdom on managing surface, flood, and subsurface flows, it is in soil water management that the traditional water culture of this Mediterranean region implements its more effective adaptive practices (terracing, adapted crops). Current land abandonment is perceived as a major driver of landscape change threatening this traditional system. Abandoned agricultural areas are transforming into xerophytic shrub covers, and walls of terraces are slowly eroding into the river. A key question for the maintenance of long-term water supply is the combined effect over water funds of three processes: climate change/drought periods, collapse of traditional land uses, and evolution of vegetation. Because BalanceMed does not model erosion, other eco-hydrological models like the soil and water assessment tool (SWAT) could be more suitable for further detailed estimations of the impact of agricultural abandonment on erosion rates. Other works have successfully applied this model in Mediterranean catchments to address this interaction in relation to water flows quality and quantity either on a historical basis (Glavan et al. 2013a, b) or to compare management scenarios (Glavan et al. 2012).

We not only found a marked spatial gradient on water supply and demand, but also on impacts to water bodies. The Alto Andarax contains healthy ecosystems protected by the park. Our finding of high recharge rates occurring in the low permeability soils of the upper catchment supports the reported high interaction of subsurface-surface flow in this area by Sánchez-Martos et al. (2005). As also shown by Contreras et al. (2008), the North Gador Sierra area is a key provider of water recharge to the southern part of the aquifer and plays a key role supporting intensive agriculture there. This northern part of the aquifer is affected by the assessment of “poor” ecological status of the whole aquifer that our findings contravene, i.e., water tables are not lowering and water quality does not reach poor state thresholds. The almost exclusive dependence on surface water by most upstream users limits its availability to downstream users, driving groundwater stock depletion on quantity and quality at the basin outlet.

The societal metabolic pattern shows an intermediate situation between a low and a high external input agricultural system (Giampietro and Lomas 2014), common in high-mountain areas with multifunctional landscapes. Agricultural trade openness to external markets is important but does not sustain the whole economy because the services and public sectors are bigger in terms of employment. Our findings uncover the crucial role of unpaid women's work in households, indicating a more reproductive (functions fulfillment) than productive (market oriented) metabolic pattern. Ageing population poses a major challenge for continued viability of this pattern in the future. The adaptation strategy seems twofold: first, an increasing interaction with the urban downstream areas in terms of external revenues and agricultural land maintenance for leisure or supplementary rent; second, a sector of the population claims extending irrigation to increase agricultural productivity in line with the intensive agricultural model dominating in the surrounding geographical context. This is constrained by environmental objectives established at the water-governance level that require a reduction of water withdrawals.

The expectations generated over the possibility of obtaining additional resources through efficiency improvements might be counteracted by the effects of the progressive abandonment of the acequias. There is a feedback signal between technological and social transformations. The functioning of local irrigation communities has been inherently linked to the use and maintenance of the galleries and acequias system (Segura 2010). Their substitution by pipes and drip irrigation will permit automation thus reducing the time required for agricultural land maintenance, and at the same time, phasing out local institutional rules. In addition, there are ecological trade-offs. The declaration of the national park forced farmers to abandon acequias within park boundaries. A key consequence of this abandonment has been a decline in riparian vegetation living on their banks. This forced the park administration to maintain the acequias at considerable public cost. The question of whether it will be possible to increase productive water uses at the same time as complying with environmental objectives of the EUWFD will depend on (1) the willingness of local irrigation communities to adapt their institutional rules; and (2) whether the additional available water is allocated to meet ecosystem requirements or will generate a rebound effect, i.e., a further intensification of the saved water use. There is increasing literature (Dumont et al. 2013, Cabello and Madrid 2014, Sampedro and Del Moral 2014) showing that efficiency, so far, has not been effective in controlling water demand in the absence of proper monitoring and withdrawal control protocols.

CONCLUSIONS

Water resources research within complex systems requires conceptual devices capable of dealing with the epistemological implications of human-environment relationships. Among these are the multidimensionality of water systems, the multiple scales involved in water management, and the uncertainty over the evolution of feedback relationships within social-ecological systems. The SESWM has been proposed as a holistic framework for integrated analysis of sustainability of water resources management. This study is the first operationalization of this framework at the river-basin scale. We emphasize the importance of including the governance dimension because it is a key driver

shaping human-environmental interactions. The production and evolution of hydro-social landscapes are filled by a variegated set of social agents with changing and more or less acute confrontations. The diverse and changing features of water funds and flows, together with their contentious uses, demands, and imaginaries around it, are always mediated through political institutions and policy networks and regimes, including those through which access or ownership over nature and the tools of its distribution are organized.

In the particular case of the Upper Andarax, the current water metabolism is the result of centuries of social-ecological evolution. This basin is an illustrative case of European high-mountain rural areas striving to face rural exodus with an economy in transition from the agricultural to the service sector. We have shown how its societal organization is integrated within the ecosystem water metabolism and how it has influenced the eco-hydrological functioning of the basin. The observed impacts to aquatic ecosystem have some direct causes like an excess of withdrawals in dry summer periods and wastewater discharge, but also other long-term socioeconomic processes like agriculture abandonment or lack of control over extractions. From our results, we can pinpoint the following key water management challenges for the Upper Andarax: (1) the need to include soil moisture formally in water planning as the water fund providing the greatest variety of services to the social system; (2) the separation of the misleading linkage of the ecological status assessment for the North and South Gador Sierra aquifers; (3) the appropriate monitoring to ensure that efficiency improvement is a conducive strategy to meet river ecosystem requirements and additional societal demands; and finally, (4) a social-ecological approach to water governance that would require policy measures to tackle the sustainability of societal funds beyond the continuous augmentation of water flows, addressing the long-term drivers of metabolic change.

On a methodological level, we bridge the analysis of societal metabolism and ecosystem metabolism in the MuSIASEM accounting scheme on a spatially explicit basis. The analysis of ecosystem metabolism of water in river basins is proposed through the eco-hydrological processes that control water resource renewability (supply-side sustainability), the impacts caused to ecosystem health (sink-side sustainability), and the boundary concepts of water availability and ecosystem water requirements. The proposed method requires the integration of several models and multiple types of data with the associated accumulated uncertainty. We limited our eco-hydrological analysis to averaged climatic series and a snapshot of societal metabolism that is sufficient for descriptive purposes and linkage to water planning. Further steps of scenario building would require a more thorough analysis of historical trends as well as a higher temporal resolution for hydrological calibration. In addition, we focused our analysis on provision services of water but the inclusion of cultural and regulating ecosystem services is suggested for further works. Further research in the area can focus more specifically on (1) relevant linkages between land abandonment, erosion, and their impact on aquatic ecosystems; (2) efficiency improvement and its impacts on aquifer dependent systems; and (3) conflicts between local and regional scales of water governance.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/issues/responses.php/7778>

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Appendix 1

This appendix has the purpose of extending the methodological description including detailed calculation of variables and modeling validation.

Scales

Even though watersheds are the object of study of hydrology par excellence, they are not in societal metabolism of water. One of the main reasons is the scale mismatch on available data. Economic variables are crucial to study the self-organization of social systems. These are not usually available at the exact boundaries of a catchment and have either to be aggregated from lower administrative divisions (municipalities or similar), or disaggregated from upper ones. Focusing on the watershed level we gain connection with eco-hydrological processes and water governance but we lose the capacity to delve in the economic relations within the social system. To this purpose, administrative units are more appropriate as analytical extent (see for instance Madrid et al. 2014).

Agriculture is commonly the main water consumer in a river basin and the societal metabolism approach to agro-ecosystems is the rural systems analysis (Ravera et al. 2014, Serrano and Giampietro 2014). It focuses on the allocation of land and human activity in terms of time use of rural households and the associated production and consumption of biophysical and monetary flows (Scheidel 2013). These studies are usually carried out at local scales, gathering data and building metabolic typologies on a bottom up basis through surveys to farmers and households. The size of a river basin and the necessary consideration of urban water require coarser modeling resolutions.

River basins are always middle scales, between the social and hydrological, between the local and the regional, between the rural and the urban. Allen and Hoekstra, 1992:64 shed light on the problematic with middle scales: “these have too many parts to model each one separately, but not enough to allow averages that fully subsume the individuality of the part. Questions that cannot be answered imply a middle number system specification. They are unpredictable because the constraint structure is unreliable. [...] At middle scales, each part of the landscape has its own individual explanation”. The multi-axes holarchic representation (Figure 2b of the paper) is an attempt to escape this middle scales dialectic. Any holon results from the composition between the observed system and the observer interests. We set the organizational levels for our system, and with them the relevant parts of the system that we want to observe. There is a tendency to augment the size of the system and thus its spatial extent with the level, but holons can be analyzed at any temporal and spatial scale (we can study a rock holding it with our hand or looking through a microscope). Main constraints are data availability and modelling capacity.

Figure 1 shows the temporal and spatial levels used for the Upper Andarax grammar according to these constraints. We run the BalanceMED model on temporal monthly and spatial Hydrological Units (HU) resolutions. Results were aggregated to the extents of one year and land uses and covers types. Socioeconomic data are available for a variety of grains (see Table 1). Human activity is mapped for whole urban areas (municipal level) and agricultural land uses for irrigation

communities and rain-fed agriculture polygons. Note that we could do a municipal level analysis (comparing each municipality Land-Human activity budgets) but this would enlarge the amount of results and loose the purpose of the study: the operationalization of the SESWM framework for the analysis of water management at river basin scale. As Schneiel 2013 explains “every kind of data collection is always a ‘heroic simplification’ of a complex rural system and the issue is rather to find the adequate simplification, which allows answering some relevant research question”. A more detailed hydrological resolution and, especially, temporal series of water use would clearly improve the method analytical potential.

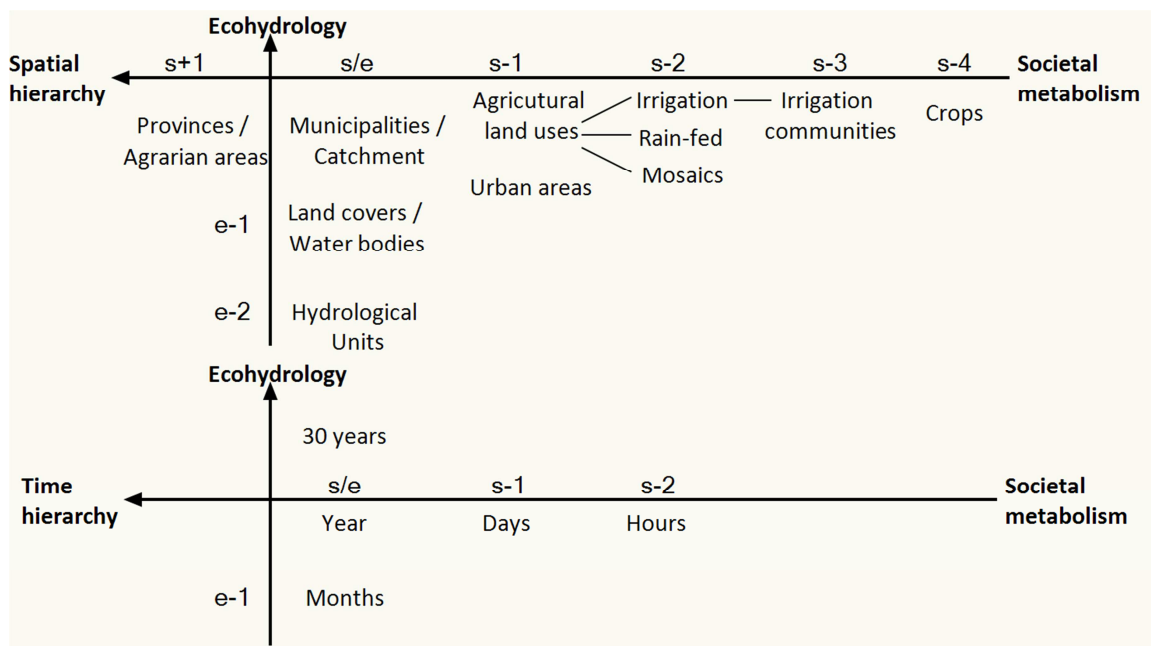


Figure 1- Temporal and spatial hierarchies in the Upper Andarax water grammar

Conceptual model and formal categories

The conceptual model for variables calculation is presented in Figure 2 and the formal categories of the grammar in Table 1. Codes and databases can be downloaded here:

https://www.dropbox.com/sh/45za6hqmnjelqoi/AAD-ObuilYtGzFwVKyJ_WzQ5a?dl=0

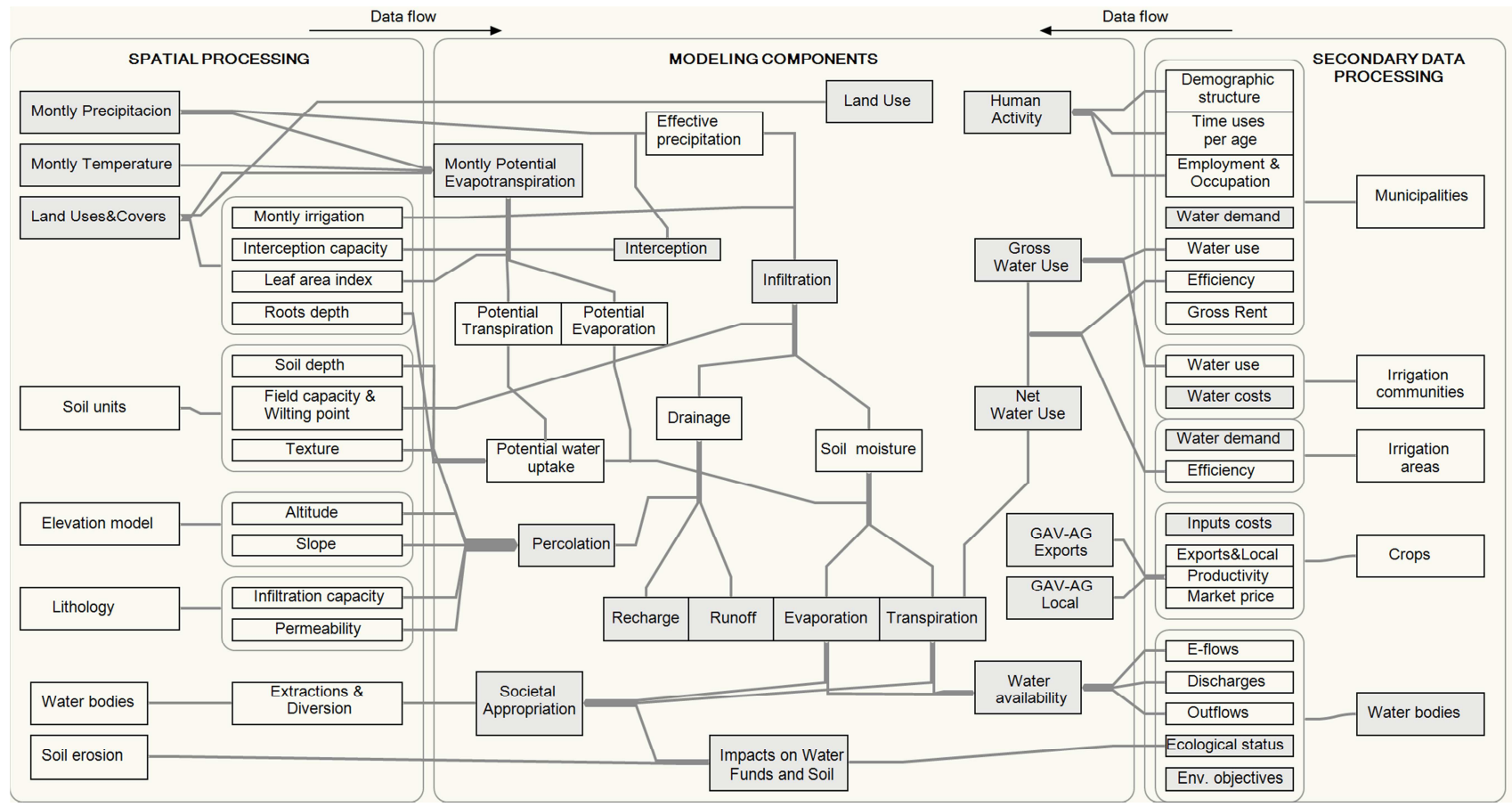


Figure 2 - Conceptual scheme for water grammar formalization

Table 1- Formal categories of the water grammar

<i>Semantic categories</i>	<i>Types</i>	<i>Description</i>	<i>Units</i>	<i>Temporal resolution</i>	<i>Spatial resolution</i>	<i>Data sources</i>
Water exchange						
Climate	Precipitation	Average precipitation from the series 1970-71/2000-01	mm/Hm ³	Months	Raster 10 m	Secondary Climatic Stations National Network (8)
Water funds turnover	Runoff	Total runoff to surface water bodies	mm/ Hm ³		HU	BalanceMED
	Recharge	Infiltrated rain water that percolates to aquifers				BalanceMED, APPLIS recharge model
	Soil Infiltration	Infiltrated rain water that is evapotranspired or contributes to soil reserve		BalanceMED		
Societal appropriation & Availability	Surface	Direct diversion from the river for human uses	Hm ³	Year	Municipalities & Irrigation communities	(1), (2), (3)
	Groundwater	Extractions from aquifer	Hm ³			
	Soil water	Soil moisture in land used by humans	mm/ Hm ³	Months	HU	BalanceMED
Gross water use	Withdrawn	Ground and surface water consumption	Hm ³	Months	Municipalities & Irrigation communities	(1), (2), (3)
	Soil	Evapotranspiration from land uses		Months		
Net water use	Urban supply	Water supply*Efficiency in supply chain	Hm ³	Year	Municipalities	(1), (2)
	Food production	Water withdrawal for agriculture*Efficiency in supply chain*Efficiency of irrigation system + Transpiration from rain water		Months	Agricultural areas & Irrigation communities	(1), (4), (5)
	Forestry & Esparto gathering	Transpiration from rain water		Year		
	Cattle	Surface water requirements + transpiration from rain water		Year	Watershed, land cover	(1), BalanceMED
	Loses	Gross Water Use minus Net Water Use		Year	Municipalities & irrigation areas	(1), (2), (3)
Water demand		Deficit for irrigation purposes in the RBMP		Year	Irrigation areas	(1)
Water rights		Authorized withdrawals from each water		Year	Water bodies	(1)

		body				
Organization						
Climate	Temperature	Average precipitation from the series 1970-2001	°C	Months	Raster 10 m	Secondary Climatic Stations Network (8)
Water bodies	Rivers Aquifers	Descriptive category: water bodies types considered in the RBMP	-	6 years	6 years	(1)
Land covers		Surface occupied by land cover types	Hectares	4 years	Land cover polygons	Map of Land Uses and Covers of Andalusia 2003 (9)
Managed land uses		Surface occupied by land uses types under managed land	Hectares	4 years	Land use polygons	
Human activity	Physiological overhead Social, Leisure & Education Unpaid work Paid Work	Hours devoted to personal care, eating, sleeping and dependent people time Hours devoted to traveling, leisure activities, education and volunteering Hours devoted to households work Hours devoted to each type of paid work sector by the working population	Hours	Hours	Municipalities	Time Use Survey of Almeria province 2002/03 (10) Spanish Population and Households Census 2001 (11) Local population census 2005 and 2011 (10)
Technical capital	Hydraulic infrastructures Irrigation technology	% of surface of irrigation communities supplied by acequias % of surface of irrigation communities with drip irrigation	%	Year	Crop types	(3)
Monetary exchange	Agricultural inputs & Water costs	Total expenditures of irrigated agriculture on water and other inputs	€			Crops types & Irrigation communities
	Gross Added Value	Total income from local and external markets			Crops types	(3), (6)

- (1) CMAT 2012. Andalusia Mediterranean River Basins Management Plan 2009-2015. [online] URL: <http://www.juntadeandalucia.es/medioambiente/site/porta/web/menuitem.7e1cf46ddf59bb227a9ebe205510e1ca/?vgnnextoid=6d3173f2c746a310VgnVCM200000624e50aRCD&vgnnextchannel=0bb66af68bb96310VgnVCM100001325e50aRCD>
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- <http://www.juntadeandalucia.es/agriculturaypesca/sigregadios/servlet/regadios>
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 - (5) CA 2011. System of technical assistance to farmers of the Andalusian government. [online] URL: <http://www.juntadeandalucia.es/agriculturaypesca/ifapa/sar>
 - (6) CMAT 2006. Andalusia Multiterritorial Information System. [online] URL: <http://www.juntadeandalucia.es/institutodeestadisticaycartografia/sima/index2.htm>
 - (7) CA 2005. Annual statistics on agriculture and fishing of Andalusia. [online] URL: <http://www.juntadeandalucia.es/agriculturaypesca/portal/servicios/estadisticas/estadisticas/agrarias/resumen-anual.html>
 - (8) AEMET. Spanish State Agency of Meteorology. [online under payment] URL: <http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos>
 - (9) REDIAM. Andalusian Network for Environmental Information. [online] URL: <http://www.juntadeandalucia.es/medioambiente/site/rediam>
 - (10) IECA. Andalusian Statistical and Cartography Office. [online] URL: <http://www.juntadeandalucia.es/institutodeestadisticaycartografia>
 - (11) INE. Spanish Statistical Office. [online] URL: <http://www.ine.es/jaxi/menu.do?type=pcaxis&path=%2Ft20%2Fe242&file=inebase&L=0>

BalanceMED

Precipitation and potential evapotranspiration

GIS raster layers of average monthly precipitation and potential evapotranspiration (PE) variables were obtained from the Andalusian Network for Environmental Information (REDIAM) for the period 1971-2000. Monthly scale reflects better the normal Mediterranean environmental conditions due to the usual lack of rainfall in finer time scales generated by long periods of water deficit. This source of information was chosen because it is the same used by the River Basin Authority for hydrological modeling. We found hydrological variables (runoff and recharge) were greatly overestimated using this data source. Mean values are usually not representative when dealing with very irregular regimes with skewed precipitation density functions such as the ones in the Andarax. In arid and semiarid climates, the median as central statistic measure is more robust. For this reason, median monthly values were obtained at the closer 24 meteorological stations with available data for the 1971-2000 period (within a buffer of 10 km). These stations belong to the Spanish State Agency of Meteorology and only provide temperature and rainfall data. PE was estimated using an excel macro based on Thornthwaite method (HydroBio3, Camara and Martinez 2002). All data series were then spatialized using the Inverse Weighted Distance interpolation in ArcGIS 10.2 to obtain continuous information to be entered in the model. Results significantly improved making estimates closer to real conditions.

Hydrological units processing

Hydrological units are obtained from the intersection of soil and land cover GIS layers. Previously, several parameters were calculated for each of them. Roots depth, Leaf Area Index and interception capacity were gathered for vegetation species through literature review. Weighted means per number of species were obtained for each land cover unit. Soil parameters are wilting point, field capacity and soil depth. These are calculated from data on lime, clay and organic matter fractions extracted from the soil cartography of the Desertification Prevention in the Mediterranean Project (LUCDEME) of the Spanish Ministry of Agriculture.

Percolation

The APLIS equation was proposed by Andreo et al. 2004 for determining the average rate of recharge in carbonate aquifers. This rate is expressed in BalanceMED as a percentage of drainage for each hydrological unit and calculated as:

$$R(\%) = (A + S + 3L + 2I + S)/90$$

Where A is the Altitude, S is the Slope, L is the Lithology, I the preferential Infiltration layers and S the Soil. Punctuation categories are established for each variable between one (minimal influence in recharge) and ten (maximum influence). In our study, slope was corrected to zero for agricultural land uses in order to introduce the leveling effect of terraces. These parameters are averaged for HU grain.

Model calibration, validation and limitations

A detail description of BalanceMED can be found in Willaarts et al. 2012. For this study, the model was translated from a Microsoft Excel macro to an R script to gain flexibility for future implementations. Model calibration was done through standard hydrograph plot (Figure 3). Monthly volumetric runoff rates are recorded at the only one available gauging station in the basin for the time series 1971-2000. Mean-monthly values of observed runoff were contrasted against model runoff. The peak of runoff in April responds to the monthly precipitation pattern but is not

observed in the gauging station likely because it is the month were irrigation starts and pools are filled with diversions from river.

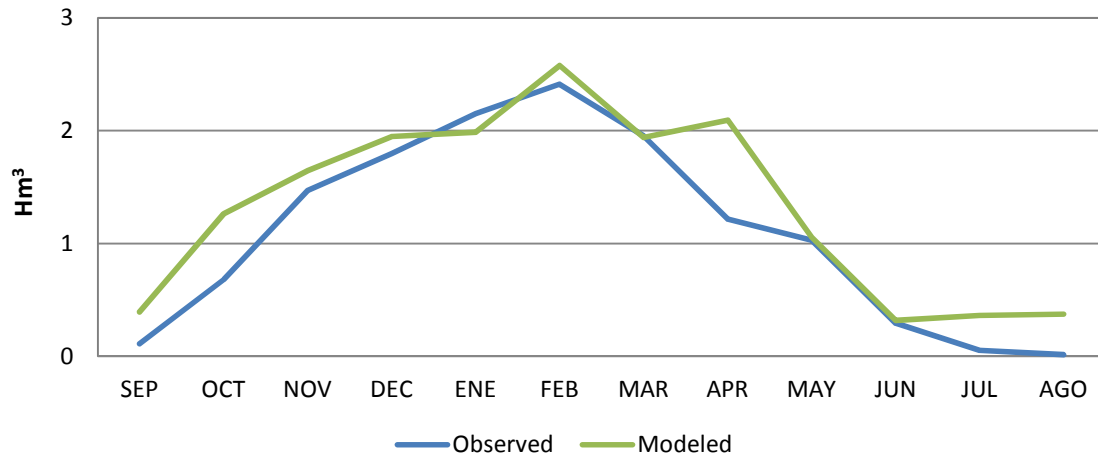


Figure 3 - Plot of observed vs modeled runoff volumetric rates

In order to validate results, the evaluation statistics recommended by Moriari et al. 2007 were used: (i) the Nash-Sutcliffe efficiency (NSE) which indicates how well the plot of observed versus simulated data fits the 1:1 line, (ii) the Percent bias (PBIAS) which measures underestimation tendency of the model and (iii) the RMSE-observations standard deviation ratio (RSR), which is a standardized version of the root mean square error. The model performance can be judged as satisfactory according to these criteria (NSE > 0.50 and RSR < 0.70, and if PBIAS ≤ 25% for streamflow) (Table 2). The model efficiency shows a good plot fit between observed and simulated data. The PBIAS indicate a slight overestimation of runoff.

Table 2 - Model evaluation of BalanceMED. Three metrics were calculated to validate model results: Nash-Sutcliffe efficiency (NSE) (range = $-\infty/1$, optimum 1); Percent bias (PBIAS) (range = $-\infty/+\infty$, optimum 0); and RMSE-observations standard deviation ratio (RSR) (range = $0/+\infty$, optimum 0).

Statistics	Value
NSE	0.80
PBIAS	12.00
RSR	0.44

Post processing water grammar variables

Main results from BalanceMED are the volumetric variables of recharge, runoff, soil infiltration, transpiration and evaporation on a monthly and HU resolution. Intensive variables (mm or m³/ha) used for spatial analysis of ecosystems-water funds relation are obtained by weighted means per area for each type of LULC considered. Extensive volumetric variables (total Hm³) were obtained by aggregation per HU area.

Societal metabolism

Human activity

A thorough description of human activity accounting can be found in Kovacic and Ramos-Martin 2014. The Total Human Activity in a given society is calculated in hours as:

$$THA_{year\ i} = 365 * 24 * Population_{year\ i}$$

This total is disaggregated in subsequent hierarchical levels according to case-study objectives. In our case, the categories considered are explained in Table 1 and the equation to valid is:

$$THA_{2005} = HA_{PO} + HA_{SLE} + HA_{UW} + HA_{PW}$$

Where *PO* is physiological overhead; *SLE* is social, leisure and education; *UW* is unpaid work; *PW* is paid work. These variables were calculated for each municipality with data on employment, occupation, education and demographic structure from Spanish Census of Population and Households 2001 and the Time Use Survey 2002-03 for Almeria province. This latter establishes shares of hours devoted to the different activities in a day per age ranges. Since that information is only available every ten years in Spain, the obtained human activity shares were then extrapolated to the population evolution until 2005. Considering there was not mayor societal changes those years (pre economic crisis 2008 scenario), it is a reasonable assumption. The new census 2011 collected data from 2011 to 2013 and did not reach the same detailed level of municipality for required data inputs. For this reason it is not possible to update the human activity budget.

Land uses

Two geographical layers were used for the land budget analysis: the Map of Land Uses and Covers of Andalusia 2003 (MLUCV03) and the Inventory and characterization of irrigation in Andalusia 2008 (ICIA08). This latter collected data through surveys to Irrigation Communities from 2002 to 2008 and is the baseline used for the RBMP. It contains crops surface per irrigation community. Categories of irrigated agriculture in the MLUCV03 were coerced to match those of the ICIA08. For the rest of land uses and covers, we broke the hierarchical structure of the MLUCV03 in order to group them in types and levels relevant our analysis. MLUCV03 was intersected with the parks boundaries to obtained categories of land management. For each type of LULC and protection category (High protection in the National Park, Medium protection in the Natural Park, no protection in the rest of the watershed) a land use ratio was assigned as shown in Table 3.

Table 3 – Land and soil water use coefficients.

	High protection	Medium protection	Not protected	Water uses
Irrigated agriculture	1	1	1	Irrigated agriculture
Rainfed agriculture	1	1	1	Rainfed agriculture
Abandoned	0	0	0.2	Grazing
Quercus forest	0	0.1	0.2	Forestry
Pine plantations	0	0.1	0.2	Forestry
Riparian forest	0	0	0	
Shurbs	0	0.2	0.3	Grazing (2/3) and

				gathering (1/3)
Pastures	0	0.3	0.5	Grazing
Urban	0	1	1	Urban supply

Monetary flows and technical capital

Crops economic data and irrigation infrastructures were also double-sourced:

- Irrigated crops: Gross Added Value/ha, Working Days/ha, agriculture Inputs Costs/ha and Water Costs (cent €/m³) were obtained from ICIA08. The type of trade (exports, local or self-consumption) and water supply and irrigation systems are also included in this database. Total extensive variables were obtained for each type of crop and trade.
- Rain-fed crops: production in Tons/ha per type of crops and prices received by farmers in €/100 kg were obtained from the annual statistics on agriculture and fishing of Andalusia 2005. Total Gross Added Value per crop was estimated based on the surface of rain-fed agriculture land uses.

There is no available data of added value for other economic activities than agriculture at municipal level. The total Gross Rent in the basin is calculated aggregating for each municipality rent per capita.

Water use

Water withdrawals and use were obtained from three sources:

- The Andalusia Mediterranean River Basins Management Plan 2009-2015, which includes extraction from different sources, water allocation to different uses and average irrigation efficiencies.
- The Inventory and characterization of irrigation in Andalusia 2008– ICIA08 contains data on gross water use for each irrigation community from different sources. Net water use was estimated by multiplying for the average efficiency in their area.
- The report from Martinez 2011 is the only data source with actual urban gross and net water use measured data for all municipalities in the Almeria province as well as water sources.

These variables are provided for one year. For seasonal analysis, monthly irrigation was estimated based on schedules from the technical assistance to farmers system of the Andalusian government and personal communication from farmers in the area. Multi-crops areas were averaged. Urban water was broken into equal monthly shares for residents and commercial uses and non-residential use was added to summer months. Water withdrawals were spatialized by splitting the river length in segments according to water withdrawal points by each municipality and irrigation community. Soil water use is calculated applying the same coefficients of land covers use and relating them to activities presented in Table 3. Gross water use is the total evapotranspiration and net water use is transpiration in those covers. The separation of transpiration from irrigation

and from rain water was obtained by the difference between running the model with and without irrigation.

Ecosystem health

The assessment of the ecological status of water bodies is the baseline of the RBMP. Aquifers are evaluated on their quantitative (exploitation index) and qualitative (pollution) status. Rivers are evaluated on their biological (biodiversity), hydro-morphological and physico-chemical status. The information provided in the plan is rather dated (only one sampling campaign) and the final evaluation based on expert evaluation. We provide additional analysis of available secondary data to complement and discuss this assessment: erosion rates, water table levels and surface and groundwater quality.

The cartography of average erosion rates for the period 1992-2006 is available at the natural hazards section of the Andalusian Network of Environmental Information [Online] URL: <http://www.juntadeandalucia.es/medioambiente/site/rediam/portada/>. The calculation method used by the Andalusian Environment Agency is the Universal Soil Loss Equation (USLE) and the scale set by this institution by normalizing the range of average soil losses values in the region from low (<12 ton/ha yr) to high (>50 ton/ha yr). Water table levels change was also averaged for the available series from 1992-2006 from the network of piezometers of the Spanish Institute of Geology and Mining Water Database [Online] URL: <http://info.igme.es/BDAgua/>. There are more control piezometers but only 32 have data and 22 data for the selected period. Most series stop in 2004 and there is no data afterwards in this database. The Spanish Ministry of Environment has been monitoring only 9 of them from 2006 on. The decrease in water table monitoring points is therefore considerable. Groundwater and surface water quality variables have been downloaded from the Andalusian River Basins Network for physico-chemical and biological control of water quality, which contains all the sampling campaigns from 2002 to 2013 [Online] URL: http://laboratorioediam.cica.es/Visor_DMA/?urlFile=http://laboratorioediam.cica.es/Visor_DMA/service_xml/capas_dma.xml]. Available series for this period for each control point were averaged.

Regarding ecosystems water requirements, land ecosystems transpiration is a result from BalanceMED, environmental flows for the river are proposed in the RBMP on a monthly volumetric rate and aquifer discharges to springs and other connected aquifers were estimated in the Hydrogeological Atlas of Andalusia 1980-1990 [Online] URL: http://aguas.igme.es/igme/publica/libros1_HR/libro110/Pdf/lib110/in_32.pdf.

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