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Improved modelling of the freshwater provisioning ecosystem service in water scarce river basins

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Freshwater provisioning by the landscape contributes to human well-being through water use for drinking, irrigation and other purposes. The assessment of this ecosystem service involves the quantification of water resources and the valuation of water use benefits. Models especially designed to assess ecosystem services can be used. However, they have limitations in representing the delivery of the service in water scarce river basins where water management and the temporal variability of water resource and its use are key aspects to consider. Integrating water resources management tools represents a good alternative to ecosystem services models in these river basins. We propose a modelling framework that links a rainfall-runoff model and a water allocation model which allow accounting for the specific requirements of water scarce river basins. Moreover, we develop a water tracer which rebounds the value of the service from beneficiaries to water sources, allowing the spatial mapping of the service.

Software availability

Downloads of the software used in the presented analysis are available in http://www.upv.es/aquatool/en/software_en.html.

1. Introduction

The importance that the services provided by ecosystems (ecosystem services, ES) have for human well-being has gained broad recognition in the last decade. Lately, ES have been incorporated into the political and scientific international agenda as a way to support environmental protection and the efficient use of scarce resources. Outstanding examples are the Mapping and Assessment of Ecosystems and their Services (Maes et al., 2016) that assists EU member states in mapping and assessing the state of their ES with the aim of informing the development and implementation of related policies; the Natural Capital Project (Natural Capital Project, 2016), which proposes tools and approaches to account for nature's contributions to society that are useful for decision makers; and the Intergovernmental Platform on Biodiversity and Ecosystem Services (Díaz et al., 2015), which assesses the state of biodiversity and of the ES it provides to society in response to requests from decision makers. All these big initiatives point out science-policy interaction as the way to apply the ES approach in practice. It is also in the background of these initiatives the need for bringing ES assessment to the operational level, in which planning and management of natural resources take place, in order to make the most of the ES approach and effectively advance to a more sustainable decision making. To do so, suitable tools to analyse the impact of management actions on ES are necessary (Connor et al., 2015).

In the case of water resources, the management scale is the river basin as established by the European Water Framework Directive (European Parliament and Council, 2000) and in line with the Integrated Water Resources Management paradigm (Global Water Partnership, 2000). Even though water is essential for most ecosystem processes that rely on water abundance, temporal and spatial distribution, there are only two types of ES that are related to its management. Aquatic ES account for the benefits provided by freshwater ecosystems such as water purification (Keeler et al., 2012; La Notte et al., 2012; Liquete et al., 2011; Terrado et al., 2016) and habitat for fish (Liquete et al., 2016; Sample et al., 2016). On the other hand, hydrologic ES describe the benefits to people derived from the relationship between terrestrial

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ecosystems and freshwater quantity and quality (Brauman, 2015); some examples are freshwater provision (Boithias et al., 2014; Dennedy-Frank et al., 2016; Guo et al., 2000; Karabulut et al., 2016; Terrado et al., 2014), flood mitigation (Fu et al., 2013; Watson et al., 2016) and pollution abatement (Bogdan et al., 2016; Fu et al., 2012).

Unlike aquatic ES, which are clearly related to water management, the relationship between hydrologic ES and water management is not straightforward. The biophysical processes that underpin them take place in the landscape and, thus, they are affected by landscape management in first place (Guswa et al., 2014). While this is true, the anthropocentric perspective of ES only accounts for their value as far as they provide direct or indirect benefits to people. This means that the water yielded by a landscape or the pollutants retained by its vegetation cannot be accounted for as ES if they are not beneficial for downstream humans. The use of water occurs in water bodies (i.e rivers, lakes and aquifers) whose natural flow and volume patterns are modified by hydraulic infrastructures and water management practices (Richter and Thomas, 2007). Hence, eventually, the economic value of hydrologic ES is influenced by water management. Although the extent of water management impacts in some river basins is not significant, it is very pronounced in arid and semi-arid river basins which suffer from endemic water scarcity (Grafton et al., 2013; Richter and Thomas, 2007). For this reason, the assessment of hydrologic ES in this kind of river basins should take into account the influence of water management when the objective is providing reliable and accurate information for decision making.

Bearing the above in mind, the selection of the model to assess hydrologic ES in water scarce river basins should be thorough. Simulation models especially designed for ES assessment, or ES tools, integrate ecological and economic aspects for several ES considering their spatial variability (Bagstad et al., 2013a). They allow analysing tradeoffs between ES under different scenarios and are attainable for non-experts (Terrado et al., 2014). An extensive review of ES tools can be found in Bagstad et al. (2013a). The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Tallis et al., 2013) is likely the most widely known ES tool. It is a spatially explicit model to estimate levels of different ES benefits in a static timeframe, usually an average year (Terrado et al., 2016). InVEST includes freshwater provisioning, sediment retention, and water purification as hydrologic ES. It accounts for the processes taking place in the landscape considering simplified hydrological relationships whose main input are land use-land cover maps linked to biophysical parameters such as roots depth and retention capacity of vegetation. The instream processes are also simplified and limited to the conveyance of water to its use location, without regarding the influence of water infrastructures and their operation.

Another well-known ES tool is the web-based Artificial Intelligence for Ecosystem Services (ARIES) (Villa et al., 2014). It applies a probabilistic Bayesian network approach which uses a library of models and spatial data to quantify ES flows and uncertainty when little data is available (Bagstad et al., 2013b), but it also allows employing biophysical relationships when enough data is accessible (Vigerstol and Aukema, 2011). The hydrologic ES addressed by ARIES are flood regulation, nutrient regulation, sediment regulation, and water supply. It works with a time step ranging from hours to years, and does not value the ES in economic units (Villa et al., 2014). Even though this ES tool is flexible to introduce instream processes, it lacks the capabilities to faithfully represent water management influence on the delivery of hydrologic ES. Moreover, the model complexity can hinder the understanding of the modelled processes and the results for decision makers and stakeholders (Vigerstol and Aukema, 2011).

Both InVEST and ARIES, and presumably the remaining ES tools, present serious drawbacks to be used for the assessment of hydrologic ES in water scarce regions in which natural river processes are affected by the intense exploitation of water resources and changing management rules. In this context, the models traditionally used for Integrated Water Resources Management (IWRM) are a good alternative to ES tools. The integrative approach of these models aim at realistically representing hydrological processes and water management effects on water availability, water quality and derived variables (Davies and Simonovic, 2011) with appropriate spatial and temporal resolution. Some examples are SWAT (Arnold et al., 1998) and HBV (Bergström, 1995) as rainfall-runoff models; SIMGES (Andreu et al., 1996) and WEAP (Yates et al., 2005) as water allocation models; GESCAL (Paredes-Arquiola et al., 2010) and QUAL2 (Chapra et al., 2005) as water quality models; and CAUDECO (Paredes-Arquiola et al., 2014b) and TSLIB (Milhous, 1990) as habitat suitability models. They have broad scientific recognition and are already in use in many water scarce river basins to support decision making (Vigerstol and Aukema, 2011). This makes them easy to adopt for ES assessments, despite that their higher complexity makes them more difficult to parameterise than most ES tools. Consequently, potential gains in accuracy should be balanced with the increase of complexity (Bagstad et al., 2013a) when it comes to applying IWRM tools for ES assessment.

This paper focuses on the assessment of the Freshwater Provisioning hydrologic ES (FPS). Brauman et al. (2007) define it as the natural process that modifies the quantity of water for extractive (e.g. drinking, irrigation and industrial uses) and on site purposes (e.g hydropower generation, water recreation and transport). The main aim of the study is proposing a modelling framework composed of IWRM models to assess the FPS with detailed consideration of water resources management impacts. The paper describes the linkage and adaptation of a rainfall-runoff model, a water allocation model and a water quality model to obtain the spatial distribution of the FPS in biophysical and economic units. To the best knowledge of the authors, a similar modelling approach has not been presented previously. The methodology is illustrated in the Tormes River Basin (TRB) in Spain, which has a predominant semi-arid climate, for two scenarios that introduce changes in the landscape and in water management with respect to the business as usual. Results demonstrate the influence of water management on the delivery of the service, which justifies the convenience of using IWRM models to make up for the limitations of ES tools in water scarce river basins.

2. Material and methods

2.1. Modelling framework

The FPS is provided by the landscape where rainfall-runoff processes take place. Terrestrial ecosystems partly determine these processes with their influence on landscape features such as water retention capacity of soils, percolation or slope. Each part of the catchment has a different capacity to generate runoff in its diverse components (surface and groundwater water resources). As water reaches rivers, lakes and aquifers, it can be withdrawn by diverse water users that obtain a benefit from it; i.e. urban, agricultural, industrial and water-related recreational uses. Therefore, any tool used to conduct the assessment of the FPS should consider all these aspects. The proposed modelling framework (Fig. 1) comprises a rainfall-runoff model (RRM) that represents the production of water resources; a water allocation model (WAM) which reproduces the use of water by the different beneficiaries of the service; economic functions (demand curves) that translate the use of water into economic benefits; and a water quality model that is