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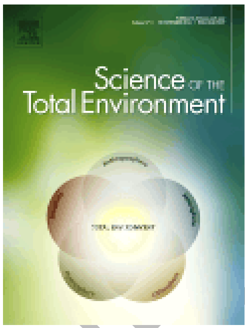

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Analysis of the uncertainty in the monetary valuation of ecosystem services – a case study at the river basin scale

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Abstract

Ecosystem services provide multiple benefits to human wellbeing and are increasingly considered by policy-makers in environmental management. However, the uncertainty related with the monetary valuation of these benefits is not yet adequately defined or integrated by policy-makers. Given this background, our aim was to quantify different sources of uncertainty when performing monetary valuation of ecosystem services, in order to provide a series of guidelines to reduce them. With an example of 4 ecosystem services (i.e., water provisioning, waste treatment, erosion protection, and habitat for species) provided at the river basin scale, we quantified the uncertainty associated with the following sources: (1) the number of services considered, (2) the number of benefits considered for each service, (3) the valuation metrics (i.e. valuation methods) used to value benefits, and (4) the uncertainty of the parameters included in the valuation metrics. Results indicate that the highest uncertainty was caused by the number of services considered, as well as by the number of benefits considered for each service, whereas the parametric uncertainty was similar to the one related to the selection of valuation metric, thus suggesting that the parametric uncertainty, which is the only uncertainty type commonly considered, was less critical than the structural uncertainty, which is in turn mainly dependent on the decision-making context. Given the uncertainty associated to the valuation structure, special attention should be given to the selection of services, benefits and metrics according to a given context.

Keywords: ecosystem management, freshwater ecosystems, ecosystem services, sensitivity analysis, human well-being, monetary values.

1. Introduction

Ecosystem services are the benefits we obtain from ecosystems, such as waste treatment by river ecosystems. These services are generated by ecosystem functions, and provide multiple benefits to human wellbeing (e.g. reduced water treatment costs, more opportunities for recreation due to a higher water quality), which in turn can be valued in either monetary or non-monetary units (de Groot et al. 2010). Specifically, the valuation of ecosystem services involves the quantification of the value of multiple benefits using the appropriate market and non-market valuation techniques, so that a value is assigned to each one of the benefits. Because of the lack of homogeneity in the non-monetary units, the values cannot be easily aggregated or compared. Thus, expressing the value of an ecosystem in monetary units appears to be useful, since this metric is meaningful to stakeholders (Costanza et al. 1997; Naidoo and Ricketts 2006; Jordan et al. 2010). Furthermore, the lack of monetary valuations has been identified as one of the underlying causes for the observed degradation of ecosystems and the loss of biodiversity (TEEB 2010).

Monetary valuations of the benefits associated with a given management action are often compared with the management action costs, thus performing cost-benefit analyses. In this context, small differences in the value of the quantified benefits might influence the decision on whether or not to perform a conservation management action (BenDor et al. 2011). Therefore, it is crucial to precisely quantify benefits of ecosystem services, and to assess and minimize uncertainty to avoid bias or even fault in decision making (Chavas 2000; National Research Council 2005; Naeem et al. 2015). The assessment of uncertainty in monetary valuations of ecosystem services is therefore crucial, but not a straightforward issue according to the literature (Turner et al. 2004; Carpenter et al. 2006; Nicholson et al. 2009; Johnson et al. 2012). According to these studies, there is a need to improve identification, quantification and communication of uncertainties in the monetary valuation of ecosystem services.

The uncertainty in ecosystem services monetary values rises from the uncertainty in the quantification of ecosystem services in biophysical units, as well as from the uncertainty in the quantification of the monetary values (TEEB 2010). Because of these two large sources of uncertainty, the monetary values might contain outstanding degrees of uncertainty (Scolozzi et al. 2012). However, the uncertainty in ecosystem services valuation is commonly ignored, or only partly considered (Seppelt et al. 2011). Seppelt et al. (2011) reviewed 153 ecosystem service studies from current scientific publications, and found that 45 % of them did not provide sufficient information regarding uncertainty in their results. Among those assessing uncertainty, most of them focused exclusively on the uncertainty in the quantification of ecosystem services in biophysical units (Johnson et al. 2012; Sánchez-Canales et al. 2012, 2015; Hou et al. 2013), despite the fact that socio-economic parameters used in the valuation process have been identified in some studies to be more relevant when quantifying the monetary values than biophysical parameters (Acuña et al. 2013). Furthermore, no clear guidelines exist on which aspects to consider when assessing uncertainty in the monetary valuation of ecosystem services (TEEB 2010; Johnson et al. 2012; Hou et al. 2013). Some attempts have been made to define guidelines, and a recent study even assembled a template to identify where uncertainty might be greatest and suggested conducting sensitivity analyses to explore the effects of uncertainty on valuation estimates all along the pathway from action to change in the value of ecosystem services related to water quality (Keeler et al. 2012). Overall, there are two types of uncertainty in the monetary valuation of ecosystem services: the structural uncertainty and the parametric uncertainty.

Structural uncertainty arises from the structure of the valuation process (i.e., selection of services, benefits, and valuation metrics), whereas the parametric uncertainty arises from the uncertainty in the parameters used in each one of the valuation metrics (i.e. valuation methods). In regards to the structural uncertainty, the decisions on the number of services and benefits to consider, as well as on which valuation metric to use are commonly, but not always, driven by the study goal and are therefore dependent on the decision-making context. Regardless of the rationale behind the selection of services and benefits, several authors pointed out the complexity of aggregating all the benefits that an ecosystem can provide while avoiding double counting the value of the same service through different benefits with a certain overlap (Arrow et al. 2000; de Groot et al. 2002; Wallace 2007; Mendelsohn and Olmstead 2009; Spangenberg and Settele 2010; Hou et al. 2013). Thus, the careful selection of ecosystem services and benefits is crucial if aiming to capture the different values an ecosystem can provide.

However, studies on ecosystem services commonly focus on too few ecosystem services, or on too few benefits per service (Acuña et al. 2013; Honey-Rosés et al. 2013). For instance, among coupled biophysical and economic models, the valuation section in the InVEST model is restricted to one or two benefit(s) per service (Tallis et al. 2011), thereby neglecting part of the monetary value of a given service, restricting the applicability of the model to certain contexts, and introducing uncertainty in the valuation. For example, the model on the ecosystem service water provisioning only considers the value of water provisioning for reservoir hydropower production (Terrado et al. 2014). Another component of the structural uncertainty relates to the choice of the valuation metric for a given benefit, as multiple valuation metrics could be applied. The choice of valuation metric has been reported to be relevant for the valuation, as different valuation metrics might be based on the same set of economic assumptions but approach the ecosystem services from different perspectives, with results varying widely depending on the choice of valuation metric rather than on the object under analysis (Spangenberg and Settele 2010; Hou et al. 2013). For example, the application of two alternative valuation metrics to the same object of measurement (willingness to pay and willingness to accept) might result in different values (TEEB 2010). Similarly, previous studies showed that different valuation metrics result in different rankings of nature-conservation value (Rouquette et al. 2009). Overall, structural uncertainty consists of decisions partly related with the context of the study, partly with data availability, and partly on practitioners subjective decisions, all of them involving that the quantification of the monetary value of ecosystem services does not deliver a unique value, but context and method dependent value estimates (Spangenberg and Settele 2010).

Parametric uncertainty relates to the uncertainty in the parameters included in the valuation metrics such as the market prices of agricultural products, which are subjected to wide swings in value due to shifts in preferences or environmental conditions (Johnson et al. 2012). Another key parameter subject to high uncertainty is the discount rate, which is used to weigh the sequence of costs and benefits over time (TEEB 2010) and often leads to diverging long term valuation results (Ludwig et al. 2005; Carpenter et al. 2006). It is because of the uncertainty in these key parameters that parametric uncertainty has also been appointed to be critical for the valuation of ecosystem services (Woodward and Wui 2001; Spangenberg and Settele 2010; Keeler et al. 2012). Actually, most of the studies to date that have considered uncertainty in ecosystem services valuation focused exclusively on the parametric uncertainty, therefore neglecting the structural uncertainty related to the selection of services, benefits, and valuation metrics.

Given this background, our aim is to identify and quantify the different sources of uncertainty when performing the monetary valuation of ecosystem services, in order to provide a series of guidelines or potential strategies to reduce uncertainty. The considered sources of uncertainty were: (1) the number of services considered, (2) the number of benefits considered for each service, (3) the valuation metrics used to value benefits, and (4) the uncertainty in the parameters of the valuation metrics. In order to assess the relevance of these sources of structural and parametric uncertainty, we have used data from 4 ecosystem services stemming from previous modeling works in the Llobregat River basin (Sánchez-Canales et al. 2012, 2015; Bangash et al. 2013; Terrado et al. 2014, 2015). The 4 ecosystem services were: water provisioning (WP), waste treatment (WT), erosion protection (EP), and provision of habitat for species (HS)).

2. Material and methods

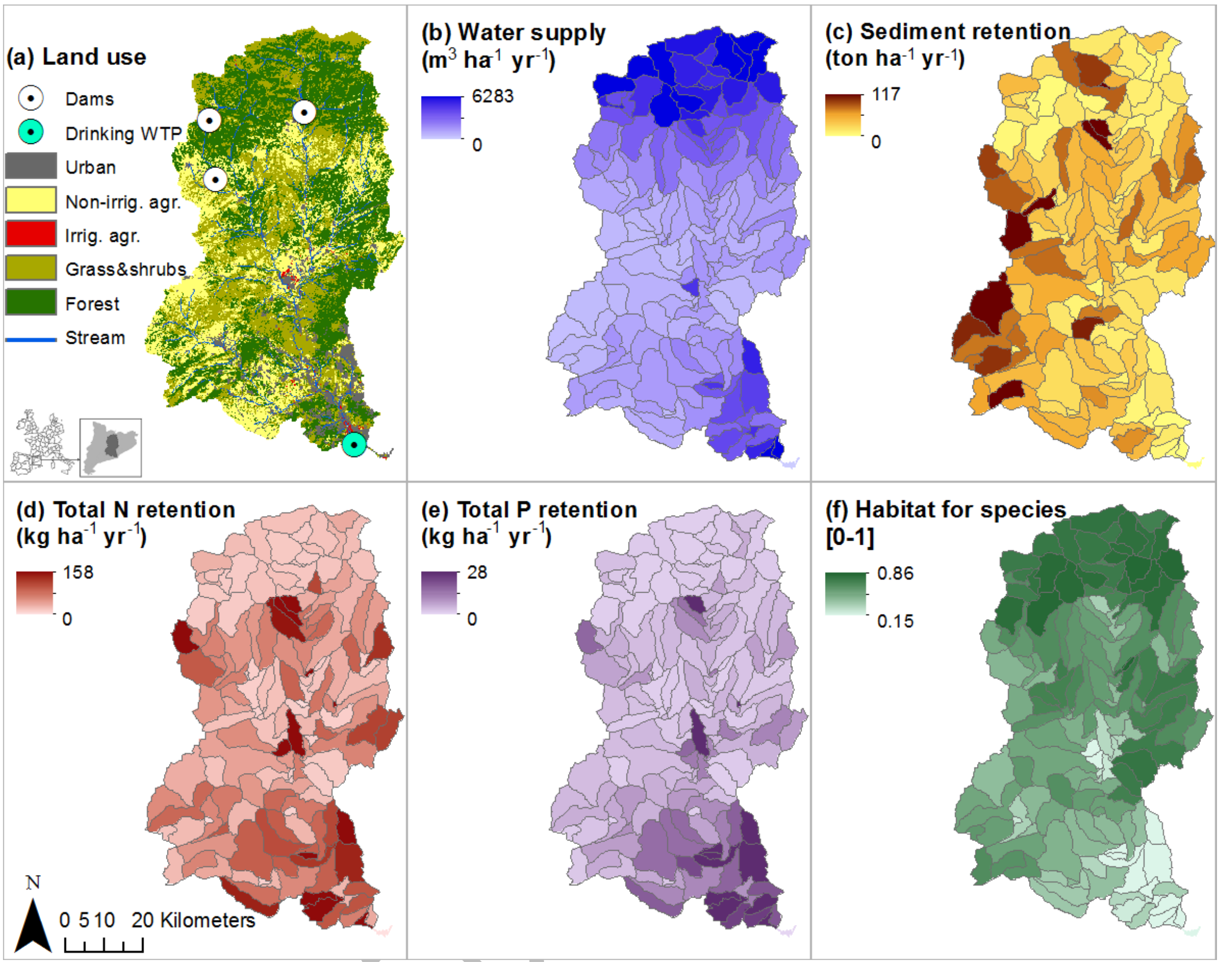

Fig. 1. Llobregat River basin: location and distribution of (a) the 5 land use classes; (b) the water provisioning ecosystem service; (c) the sediments retention ecosystem service; (d) the nitrogen retention ecosystem service; (e) the phosphorous retention ecosystem service; and (f) the habitat for species ecosystem service.

2.1. Description of the study site

The Llobregat River basin (NE Iberian Peninsula) covers an area of 4950 km^2 (Fig. 1). It is one of the main water sources for Barcelona and its metropolitan area, which have a total population of more than 3 million people. Annual rainfall varies substantially within the basin from > 1000 mm in the mountains to < 600 mm near the coast, with strong seasonal fluctuations in both rainfall and temperature. Three reservoirs are located in the upper part of the basin, and two drinking water treatment plants are located near the outlet (Fig. 1). The Llobregat River basin is an example of a highly populated, severely exploited and highly impacted area in the Mediterranean region. The basin has been long studied for several aspects, including the assessment of ecosystem services in a climate change context (Sánchez-Canales et al. 2012; Bangash et al. 2013; Terrado et al. 2014): hydrological ecosystem services in basins such as the Llobregat were shown to be very sensitive to extreme climate conditions. For instance by 2100, climate change is expected to decrease water provisioning service between 3 and 49 % and decrease erosion protection service between 5 and 43 % in this particular basin.

2.2. Ecosystem services assessment

Biophysical values of WP, WT, EP and HS ecosystem services are given in Fig. 1. The WP, WT, and EP biophysical values were calculated with the InVEST model (Tallis et al. 2011), which is a spatially explicit model consisting of a suite of models that use patterns of land use and land cover to estimate levels and economic values of ecosystem services (Nelson et al. 2009). The WP service is the amount of water drained in an area, as the difference between water from rainfall and evapotranspiration across the basin. The WT service is the amount of total nitrogen and total phosphorus removed from water across the basin. The EP service is the amount of sediments retained depending on soil erosion rates across the basin. Full details for WP, WT and EP biophysical values assessment are found in published literature (Sánchez-Canales et al. 2012, 2015; Bangash et al. 2013; Terrado et al. 2014). HS biophysical values were calculated as a function of the maximum suitability for each type of land use and land cover to provide habitat for biodiversity and different anthropogenic threats likely impairing habitat quality (Terrado et al. 2015).

For each one of these services assessed from a biophysical point of view, we considered a series of benefits, and for each one of those a series of valuation metrics in order to estimate the monetary value from each benefit (Table 1). The methods on the monetary valuation methods are extensively described in the Supporting Information, including Appendix A1, Table A1 (list of the parameters used for the monetary valuation of the 4 ecosystem services) and Table A2 (list of the equations used for the monetary valuation of the 4 ecosystem services). All values were calculated as Net Present Values (NPV) at the annual scale (2013), thus expressed in 2013 € based on the Spanish inflation rate and using the consumer price index. The uncertainty ranges for each parameter included in the valuation metrics are reported in Table A1, and were based on literature data when possible. Otherwise, ranges were based on the author's knowledge and expressed as a percentage from the parameter value, or considering an estimate error integrating the possible measurement errors, or the possible spatial and temporal variability, or the variability in possible measurement techniques.

2.3. Structural uncertainty

The structural uncertainty arises from the structure of the valuation process, that is, from the selection of the services to be quantified, the selection of the benefits considered for each service, and the selection of the valuation metric used for each benefit. Thus, to assess the structural uncertainty, we quantified the total monetary value of the considered ecosystems by as many combinations as possible of service - benefit - valuation metric (Table 1). Specifically, the uncertainty related to the number of considered services was assessed calculating a total monetary value using all possible combinations of 1, 2, or 3 services. Thus, using the combinations of 1 ($n = 4$), 2 ($n = 6$), and 3 ($n = 4$) services, we calculated a total monetary mean and coefficients of variation. Similarly, the uncertainty related to the number of considered benefits per service was assessed calculating a total monetary value with 1, 2, or 3 benefits for each one of the 4 considered ecosystem services. This allowed the calculation of 3 total monetary value means and respective coefficients of variation based on 30 combinations for 1 benefit per service, 30 combinations for 2 benefits per service, and 10 combinations for 3 benefits per service. Finally, the uncertainty related to the choice of the valuation metric was assessed calculating a total monetary value with as many different valuation metrics as possible for each one of the considered benefits, namely 128 combinations of metrics, and then calculating the total monetary value mean and its coefficient of variation.

2.4. Parametric uncertainty

The effects of the uncertainty of the parameters used in the valuation metrics on the total monetary value was assessed by running Monte Carlo simulations (a total of 3000 simulations were sufficient to obtain stable estimates of the coefficients). The space of parameter ranges was explored by random sampling from the Probability Density Functions (uniform distributions) of the parameters with upper and lower bounds defined according to literature and expert knowledge in a few cases. The uncertainty ranges (Table S2) reflected the potential variation of the parameters along the studied year (e.g. CO_2 market price) or the spatial variability within the catchment, region or country (e.g. price of drinking water). For parameters estimated from complex calculations reported without an uncertainty range (e.g. treatment cost per unit of nitrogen) we assumed a 40 % uncertainty. For land-cover related parameters a 5 % error was assumed. Thus, a Monte Carlo run (of 3000 simulations) was performed for each of the 128 possible model structure combinations, and the median and coefficient of variation of the obtained total monetary values of the 128 runs were used to quantify the parametric uncertainty.

A sensitivity analysis was conducted to evaluate the influence of the parameters of the valuation metrics on the total monetary value. We used the 3000 simulation runs to fit a multivariate linear model relating the total monetary value (Y) to the parameters of the model (X_i) (equation 1). The standardized regression coefficients β_i^2 are obtained by normalizing the slopes b_i (equation 2) (Saltelli et al. 2005) after running Monte Carlo Simulations (Corominas and Neumann 2014):

$$Y = \sum b_i \cdot X_i + a \tag{1}$$

$$\beta_i = b_i \cdot \frac{\sigma_{X_i}}{\sigma_Y} \tag{2}$$

The standardized regression coefficients β_i are a valid measure of sensitivity if the coefficient of determination R^2 is higher than 0.7 (Saltelli et al. 2004). The β_i^2 approximates the first-order variance contribution of the operational variable X_i to the Y. The analysis was repeated for each one of the 128 combinations of valuation metrics and the median of the β_i^2 was calculated for each parameter (the median of each parameter was calculated only for the β_i^2 values of the model structures in which the parameter was involved). We quantified the β_i^2 and classified parameters with $\beta_i^2 > 0.05$. Additionally, a statistical hypothesis test was performed for each regression coefficient b_i. The Student's t-test is intended to reject the null hypothesis H_0 that the coefficient b_i is not statistically different from zero; if the null hypothesis H_0: $b_i = 0$ is not rejected, then b_i could be excluded from the regression model (Montgomery 2009), and hence the associated model parameter could be excluded from the calibration.

3. Results

3.1. Monetary valuation of ecosystem services in the Llobregat River basin

Estimates of the monetary values of ecosystem services in the Llobregat River basin are given in Table A3. The values of the benefits related to WP range from 0.6 to 279 M€ yr^{-1}. Within WP, the benefit "Water for irrigation purpose" is valued between 0.6 and 87 M€ yr^{-1} depending on the valuation metric. The values of the benefits related to WT range from 3 to 182 M€ yr^{-1}. Within WT, the benefit "Higher surface water and groundwater quality" is valued between 3 to 69 M€ yr^{-1}. The values of the benefits related to EP range from 0 to 49 M€ yr^{-1}. The value of the benefit "Avoided soil losses" is about 0.8 M€ yr^{-1} regardless of which valuation metric is used. The same is observed for the benefit "Extension of water management infrastructures lifetime", which is about 8 M€ yr^{-1} regardless of the used valuation metric. The values of the benefit related to HS range from 0.001 to 351 M€ yr^{-1} depending on the valuation metric, and the willingness to pay (WTP) for the existence and conservation of genetic and species diversity (351 M€ yr^{-1}) is much higher than actual public investments (15 M€ yr^{-1}).

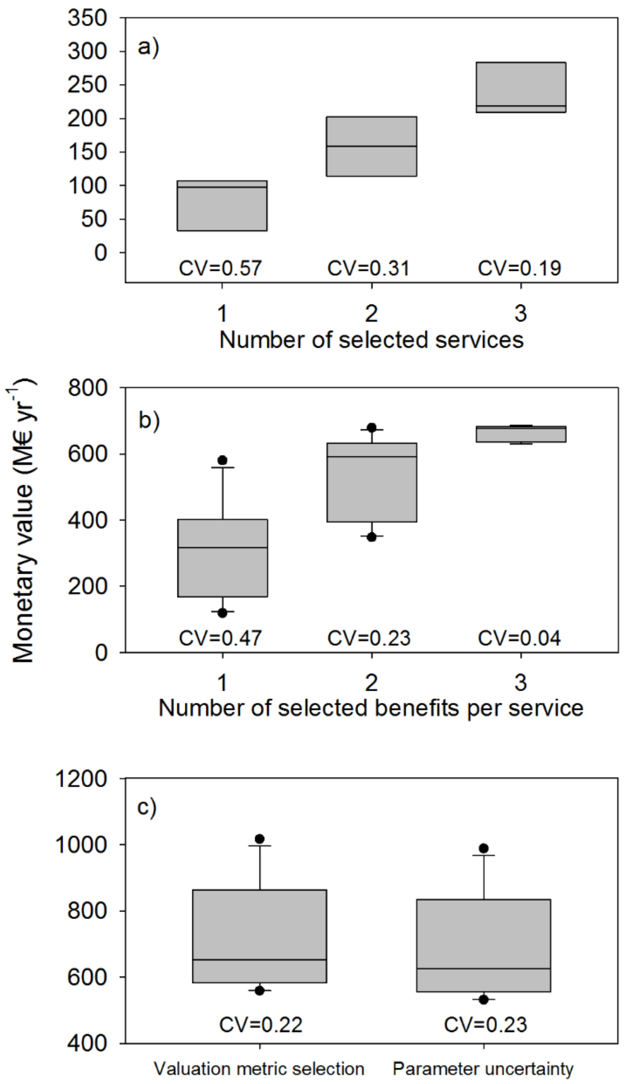

Fig. 2. Box-plots of the uncertainty of the economic value of the case-study basin given (a) the effect of the number of services selected; (b) the effect of the number of benefits selected per service; and (c) the effect of the choice of the valuation metric and of the value of the parameters included in each valuation metric. A coefficient of variation (CV) is given for each box-plot.

3.2. Structural uncertainty

The effects of the selection of services, benefits, and valuation metrics are shown in Fig. 2. Regarding the selection of services, Fig. 2a shows the possible economic value ranges considering 1, 2, or 3 services. The average value for 1 service is 79 M€ yr^{-1} (CV = 0.57), the average value for 2 services is 158 M€ yr^{-1} (CV = 0.31), and the average value for 3 services is 237 M€ yr^{-1} (CV = 0.19). Thus, the more services included in the monetary valuation, the higher the total monetary value and the lower the coefficient of variation.

Regarding the selection of benefits, Fig. 2b shows the possible total monetary value range depending on the number of benefits considered for each service (here between 1 and 3 benefits) (Fig. 1). The average value for 1 benefit is 316 M€ yr^{-1} (CV = 0.47), the average value for 2 benefits is 541 M€ yr^{-1} (CV = 0.23), and the average value of 3 benefits is 662 M€ yr^{-1} (CV = 0.04). As for the selection of services, the more benefits per service included in the monetary valuation, the higher the average monetary value and the lower the coefficient of variation. The number of benefits included in the valuation of each service varies from one service to another (e.g., from 1 for HS to 5 for EP), mainly because of the availability of data to calculate the related benefits according to at least one valuation technique. It highlights that for each service, the greater the number of services and benefits per service that are considered when quantifying the monetary value, the higher the monetary value and the lower the uncertainty.

Regarding the choice of valuation metric, Fig. 2c shows the monetary value range depending on 128 combinations of valuation metrics (see also Fig. 1 and Table S4). The mean total monetary value considering the 128 combinations is 714 M€ yr^{-1} (CV = 0.22). The number of valuation metrics that could be applied to each benefit was constrained by both data availability and valuation metrics in the literature. Consequently, benefits such as "Higher surface water and groundwater quality" and "Existence/conservation of genetic and species diversity" could be valued with 4 different valuation metrics, whereas other benefits could be valued with only 1 or 2 valuation metric(s).

3.3. Parametric uncertainty

Fig. 2c shows the uncertainty range of monetary values depending on the uncertainty of the parameters included in the equations (i.e. valuation metrics). The mean total monetary value considering the parameter uncertainty is 687 M€ yr^{-1} (CV = 0.23), almost the same as when comparing to the valuation metric selection. Actually, the interquartile range (Q3-Q1) is reduced when combining structural and parametric uncertainties.

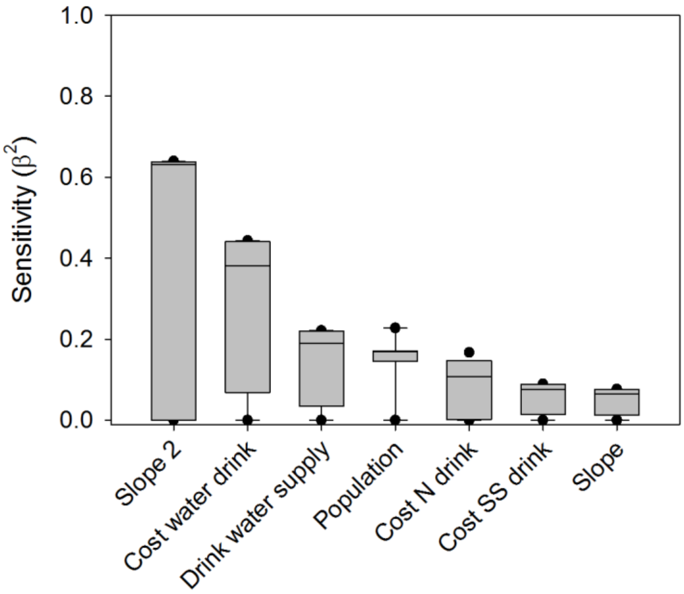

Fig. 3. Sensitivity (β_2) of the 7 most sensitive parameters (β_2 > 0.05) used to calculate the total monetary value with the 128 combinations of valuation metrics.

For the 128 possible combinations of valuation metrics, the R^2 of the multivariate linear model between the total monetary value and the parameters of each model was higher than 0.99, thus the 128 multivariate linear models were valid. Hence, the variability of each parameter depends on the parameter variation range within the sensitivity analysis and on the occurrence of the valuation metric within the combination tested. According to the median of the β_i^2 calculated for each parameter, the 7 most sensitive parameters (with $\beta_i^2 > 0.05$) were, in order of most to least sensitive (Fig. 3): (1) the slope of the willingness to pay-species richness relationship (*Slope_2*) from the benefit HS1.1; (2) the price of drinking water (*Cost_Water_Drink*) from WP1.1; (3) the amount of water diverted for human consumption (*DrinkWater_Supply*) from WP1.1; (4) the population in Llobregat (*Pop*) (a transverse parameter to WT, EP and HS); (5) the treatment cost per unit of nitrogen

(*Cost_N_Drink*) from WT1.1; (6) the treatment cost per unit of suspended solids (*Cost_SS_Drink*) from EP1.1; and (7) the slope of the water quality index - willingness to pay relationship (*Slope*) from WT2.1 and EP5.1. The Student's t-test allowed identifying parameters which were not statistically different from zero and hence, could be excluded from the linear model. This is the case for parameters with P values > 0.05, which were mainly the ones related with WP2.1, WP2.2, WP3.1, WT1.2, WT1.3, WT1.4, EP2.1, EP2.2, EP3.1, EP4.1, EP3.2, HS1.3 and HS1.4 benefits. The dispersion of the sensitivity shows that the sensitivity can change depending on the chosen combination of valuation metrics. The highest dispersion is observed for WP related parameters. These results show the wide range of sensitivity arising from the parameters used in each valuation metric between the most and the least sensitive parameters in our study case) despite the conservative range of values chosen for uncertainty assessment (see Table S2).

4. Discussion

In this study, we quantified both the structural and the parametric uncertainties in a practical exercise of ecosystem services monetary valuation. We performed the analysis using biophysical values of 4 freshwater related ecosystem services (WT, EP, HS, and WP) in the Llobregat River basin, and specifically quantified the uncertainty stemming from the number of considered services, the number of considered benefits per service, the chosen valuation metric, and the valuation metric parameters' specific uncertainty. Altogether, the total monetary value of the considered ecosystem services of the Llobregat basin ranged between 13 and 1061 M€ yr^{-1}. The quantified total monetary value in the Llobregat River basin is within the range of total monetary values one can calculate based on the biome-specific values per hectare (39 - 446 M€ yr^{-1}) (Costanza et al. 1997, 2014), and on the Iberian Foix River basin values for total emergy-based water cost including the financial, environmental, and resource costs (1873 M€ yr^{-1}) (Brown et al. 2010).

Regarding uncertainty, depending on the number of ecosystem services included in the valuation exercise, the average monetary value in the Llobregat River basin varied from 13 to 303 M€ yr^{-1} (CV = 0.48). Similarly, considering the 4 ecosystem services, and depending on the number of benefits per service, the average monetary value varied from 118 to 687 M€ yr^{-1} (CV = 0.40). In the case of the valuation metric choice, the monetary value varied between 557 and 1061 M€ yr^{-1} (CV =0.22), whereas the parametric uncertainty involved a range between 530 and 1034 M€ yr^{-1} (CV = 0.23). Therefore, looking into the uncertainty sources encompassing the entire ecosystem services valuation, we found that the highest uncertainty appears to be related to the number of services considered in the study, such that the higher the number the closer to the total monetary value of the particular ecosystem and the lower the uncertainty. The easiest advice here would be to consider as many services as possible when valuing ecosystem services, but we are fully aware that usually the number of services considered is constrained by data availability and socio-economic context, and that only a sub-set of ecosystem services might be relevant in each case study. The second most important source of uncertainty was the number of benefits considered for each ecosystem service, and lastly the choice of the valuation metric and the parametric uncertainty. Thus, our results highlight that the structural uncertainty is much higher (+8061 %; considering the total monetary value increase between its minimal value with one service and its maximal value combining services, benefits and valuation metrics), than the parametric uncertainty (+94 %; considering the total monetary value increase between its minimal and maximal values from the parametric uncertainty analysis). Accordingly, it is advisable to consider at least 2 benefits per service, as uncertainty was considerably reduced when including at least 2 benefits per service (i.e., reduction of 49 % of the coefficient of variation). Similarly, it is advisable to consider at least 2 valuation metrics for each benefit, as has also been suggested by others (Hou et al. 2013). In this sense, we are aware that different valuation metrics will often measure different things, often in different decision contexts, and thus these results vary by design. Overall, the decision to use a certain valuation metric is very context specific and relies on info about the robustness of the approach, whose values are under consideration, who the decision maker is, and obviously the services and benefits being considered. Regarding the parametric uncertainty, the uncertainty associated with the parameter values used in the valuation metrics was not negligible, as some parameters played an important role. Therefore, the sensitivity analysis to identify the relative weight of each parameter on the total monetary value with a given structure of valuation therefore seems advisable, as more effort should be placed to accurately estimate those parameters identified to be more sensitive and thus critical for the valuation of ecosystem services. For example, in our case study, a change of 10 % of the parameter *Slope2* caused a change of 1.15 % in the total monetary value.

5. Guidelines for ecosystem services valuation

Recognizing that there are different sources of uncertainty in ecosystem service valuation, and accepting that no guideline can avoid the uncertainty in the determination of the monetary value of ecosystem services, we recommend considering the following steps when performing a monetary valuation of ecosystem services in a particular decision-making context:

(i) Define the ecosystem services of interest and the linkages with the ecosystem functions that sustain them (e.g.., the water provisioning service is linked with the ecological function water balance).

(ii) Identify all benefits related with the ecosystem services of interest, benefits understood as the gains in human wellbeing.

(iii) Select as many benefits as possible among the identified benefits, as probably not enough information will be available to value all the identified benefits. If possible, consider at least 2 benefits per service, as we have found that this can significantly reduce the uncertainty in the monetary value of a given service.

(iv) Identify all potential valuation metrics related to the chosen benefits, valuation metrics understood as the functions applied to quantify the monetary value of benefits (e.g., the benefit water provisioning for irrigation can be valued through a production-based approach or through a market price metric).

(v) Select, if possible, 2 valuation metrics for each of the selected benefits. Note here that different valuation metrics will often measure different things in different decision-making contexts, so it is important that the selected ones are relevant for the given decision-making context.

(vi) Perform a sensitivity analysis to identify the most relevant parameters of the selected valuation metrics. Once identified, establish a range of values for those relevant parameters and apply the valuation metric using different values within this range (e.g., the price of water for irrigation can vary between different regions, different years or even within the year according to dry and wet periods).

Overall, the selection of services, benefits and valuation metric might be defined by a study's decision-making context, but the uncertainty of the parameters is independent from the context and, therefore, it is advisable to pay special attention to them given the relevance they have in terms of uncertainty. When defining the valuation structure, practitioners should be aware of the uncertainty inherent to the process of ecosystem services monetary valuation, and of the relevance of following each one of the recommended steps. Although the recommended guideline can reduce the uncertainty in ecosystem services monetary valuation, a measure of uncertainty should always accompany estimates of the monetary value of ecosystem services.

6. Acknowledgements

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Tables

Table 1. Benefits, endpoints, beneficiaries, valuation metrics and values of 4 ecosystem services: Water Provisioning (WP), Waste Treatment (WT), Erosion Protection (EP) and Habitat for Species (HS).

	Benefits	Endpoints	Beneficiaries	Valuation metrics	Value
Water provisioning					
WP1.1	Water for drinking purpose	Surface water	Household water consumers	Market Price	Value of water for drinking purpose
WP2.1	Water for irrigation purpose	Surface water	Farmers	Production based approach	Value of water for irrigation purpose
WP2.2		Surface water	Farmers	Market Price	Value of water for irrigation purpose
WP3.1	Hydropower production	Reservoirs	Energy producers and tax payers	Market price	Value of water for hydropower production
Waste treatment					
WT1.1	Higher surface water quality	Drinking water	Treatment facilities and tax payers	Avoided cost	Cost of water treatment for drinking purpose (contaminant removal)
WT1.2		Drinking water	Treatment facilities and tax payers	Avoided cost	Cost of water treatment for drinking purpose (contaminant removal)
WT1.3		Drinking water	Consumers	Avoided cost	Cost of health care linked to poor water quality
WT1.4		Rivers and lakes	Users and non-users	Avoided cost	Cost of ecosystem damages
WT2.1	Enjoyment of recreational areas	Rivers and lakes	Recreationists	Contingent valuation	Willingness to pay for clean water bathing areas
Erosion protection					
EP1.1	Higher surface water quality	Drinking water	Treatment facilities and taxpayers	Avoided cost	Cost of water treatment for drinking purpose (suspended sediment filtering)
EP2.1	Avoided soil losses	Land	Land owners	Replacement cost	Cost of soil restoration
EP2.2		Land	Land owners	Market price	Loss of income from productivity loss
EP3.1	Extension of water management infrastructures lifetime	Reservoirs	Reservoirs managers and taxpayers	Avoided cost	Cost of dredging dam reservoirs
EP3.2		Reservoirs	Reservoirs managers and taxpayers	Avoided cost	Cost of dredging dam reservoirs
EP4.1	Soil carbon storage	Land	Users and non-users	Market price	Value of soil carbon storage
EP5.1	Enjoyment of recreational areas	River and lakes	Recreationists	Contingent valuation	Willingness to pay for clear water bathing areas
Habitat for species					
HS1.1	Existence / conservation of genetic and species diversity	Land, stream and wetlands	Everyone	Contingent valuation	Willingness to pay for species conservation
HS1.2		Land	Everyone	Public investments	Investments in biodiversity conservation
HS1.3		Stream	Recreationists	Market price	Sale of fishing licenses
HS1.4		Land	Recreationists	Market price	Sale of hunting licenses

Appendices

Additional Supporting Information may be found in the online version of this article.

Table A1. List of the parameters used to value the multiple benefits of the 4 ecosystem services.

Table A2. List of the equations used to value the multiple benefits of the 4 ecosystem services.

Table A3. Benefit values, service values and total monetary value for the Llobregat basin.

Appendix A1. Extended methods.