Integrating ecosystem services in river basin management plans

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Summary

1. According to the European Union Water Framework Directive, river basin management plans must include a programme of measures, with a series of management actions aiming to achieve good ecosystem status of all water bodies within the basin. The design and later prioritization of these management actions is, in theory, done through cost-effectiveness analysis (CEA), which compares management action costs with expected improvements in ecosystem status. However, such an approach does not consider the effects of management actions on human well-being resulting from changes in the provision of ecosystem services.

2. We propose to complement the current CEA approach with a cost–benefit analysis (CBA) integrating the effects of management actions on the provision of ecosystem services, therefore moving from a single-objective to a multiobjective approach. We propose a flexible methodological framework based on a combination of CEA and CBA that can be easily adapted to different case studies.

3. To test the applicability of our approach, we applied it to an impaired basin, the Llobregat River basin (north-eastern Iberian Peninsula). The analysis considers management actions selected from the programme of measures under implementation: establishment of environmental river flows, improvement of river connectivity, treatment of urban wastewater and reduction in saline pollution; and the effects on a series of ecosystem services: water provisioning, waste treatment and habitat for species.

4. Results revealed that management actions designed to improve ecosystem status do not necessarily improve human well-being through changes in the provision of ecosystem services.

5. The implementation of the CEA and CBA allowed the identification of management actions providing the best trade-offs between improvements of ecosystem status and human well-being. For example, the establishment of environmental river flows in the upper Llobregat River was the management action that maximized the balance between gains in ecosystem status and human well-being.

6. *Synthesis and applications.* Overall, the combination of cost-effectiveness analysis and cost–benefit analysis supports a more informed and transparent decision-making in the implementation of river basin management plans, better assisting stakeholders to prioritize those management actions providing the optimal win–win results.

Key-words: cost–benefit analysis, cost-effectiveness analysis, decision-making, ecosystem services, ecosystem status, human well-being, programme of measures, river basin management plan, Water Framework Directive

Introduction

The management of river basins plays a key role in the conservation and improvement of the general state of water bodies world-wide because it allows for the consideration of resource protection while meeting social and

ecological needs. In the European Union, river basin management is implemented through river basin management plans (RBMPs) defined in the context of the Water Framework Directive (WFD, 2000/60/EC). The core of these RBMPs is the programme of measures, which includes a series of management actions designed to achieve good ecosystem status of all water bodies within the basin. The design and later prioritization of the management actions of the programme of measures is sometimes done through cost-effectiveness analysis (CEA) (Balana, Vinten & Slee 2011; Berbel, Martin-Ortega & Mesa 2011). CEA compares management action costs with expected improvements in ecosystem status aiming to identify those measures allowing the achievement of environmental objectives at the minimum cost. However, it has been suggested that CEA might not be the most appropriate decision-making approach (Berbel, Martin-Ortega & Mesa 2011), as it does not consider the effects of management actions on human well-being resulting from changes in the provision of ecosystem services. In fact, CEA is a single- rather than a multiobjective approach, and it does not reflect trade-offs between environmental and social objectives (Berbel, Martin-Ortega & Mesa 2011; Martin-Ortega 2012). Thus, the consideration of improvement of the ecosystem status as the unique objective in the design and prioritization of management actions may lead to undesired negative consequences for human well-being as a result of a decrease in the level of certain ecosystem services.

Given this background, we believe that the integration of ecosystem services into the design and prioritization of management actions within the programme of measures might allow to better address multibenefit goals (Everard 2014), although the practical application of the ecosystem services concept requires focusing on stakeholder needs and counting on their collaboration (Böck *et al.* 2015). In fact, the consideration of costs and benefits of measures has been progressively included in the decision-making process (Adams 2014), reinforcing the idea of nature being incorporated as an economic value in environmental decisions. Some authors have argued against the use of monetary values to weight non-market ecosystem services and biodiversity (McCauley 2006). Others have argued that intrinsic valuation of nature (i.e. that nature should be protected for its own sake) and instrumental valuation of nature (i.e. that valuation should be used in contexts where support for conservation is essential) are compatible approaches; these approaches have been proposed to comprise a unified and diverse conservation ethic (Tallis *et al.* 2014). The assessment of the effects of management actions on human well-being through the changes in the provision of ecosystem services allows the comparison of the management action costs with the economic benefits related to their implementation. Specifically, a cost–benefit analysis (CBA), performed comparing management action costs with the marginal benefits resulting from the implementation of the management actions, allows for a direct comparison of alternative management actions and provides planners more information than a CEA alone (Alcon *et al.* 2012). Although in an ambiguous way, CBA is one of the instruments that the WFD suggests to determine whether the costs of reaching certain environmental objectives are disproportionate (i.e. costs to implement management actions are too high compared to the obtained improvement in ecological status) or an extension of a deadline should be granted because environmental objectives cannot be attained by the date established in the WFD (Molinos-Senante, Hernández-Sancho & Sala-Garrido 2011). Still, numerous questions remain regarding the CBA approach. In particular, whether CBA represents society's collective well-being rather than particular interests (Turner 2007), whether economic valuation can adequately capture the complexity of people's preferences or whether CBA considers the appropriate factors when considering public benefits, including social justice (Norgaard 2010). Even acknowledging its limitations, CBA can be useful for clarifying certain trade-offs, and this has favoured its growing use by government agencies interested in quantifying the outcomes of proposed management actions. The progressive integration of economic theory and the ecosystem services concept to inform decision-making has crystallized in estimations of proportionality between the costs of implementing particular actions and the obtained benefits in the specific context of the WFD (Birch *et al.* 2010; Laurans *et al.* 2013; Vlachopoulou *et al.* 2014). The use of CBA to assess the effect of management actions has included the establishment of environmental flows or the treatment of wastewater on ecosystem services at the basin scale (Del Saz-Salazar, Hernández-Sancho & Sala-Garrido 2009; Martin-Ortega, Giannoccaro & Berbel 2011; Honey-Rosés *et al.* 2013). These studies have shown that benefits often overcome costs but also provide evidence of the large information gap between the ideal CBA and what is feasible in the context of each particular case.

In this study, we aimed to test whether the integration of ecosystem services into the design and prioritization of management actions through CBA allows for the accounting of trade-offs among different management actions and, when combined with CEA, could help prioritizing actions that provide win–win results for both human well-being and ecosystem status. Thus, we applied CEA and CBA for a series of management actions within the programme of measures of the Llobregat River basin (northeastern Iberian Peninsula). This river basin has a strong human influence and a complex management (Marcé *et al.* 2012) and therefore provides a good setting to test the complementarity of both approaches. The management actions considered address some of the most striking problems in the basin, such as the establishment of environmental river flows (the minimum flow necessary to sustain freshwater ecosystems), improvement of river connectivity, treatment of urban wastewater and reduction in saline pollution. The ecosystem services considered

include water provisioning, waste treatment and habitat provision for species. To our knowledge, few studies have relied on a combination of CBA and CEA within the framework of the WFD (Barton *et al.* 2008; Galioto *et al.* 2013), and only the latter related ecosystem services to the implementation of a programme of measures. We compared the results obtained by CBA and CEA for the selected management actions in the Llobregat and assessed whether gains in terms of ecosystem services also correspond to improvement in ecosystem status. Furthermore, we also developed a framework to link management actions of a given programme of measures with a series of benefits and monetary values that could guide similar approaches in other basins.

Materials and methods

STUDY SITE

The Llobregat River flows from the Pyrenees Mountains to the Mediterranean Sea and is one of the main water sources for the city of Barcelona and its metropolitan area, with a population of more than 3 million people (Fig. 1). Covering an area of 4950 km², the Llobregat basin is an example of a highly populated, severely exploited and highly impacted area in the Mediterranean region. More than 100 small hydropower plants are located in the basin (Fig. 1b), taking water from the river, routing it through derivation channels to the hydropower plants and returning it to the river after several metres (Marcé *et al.* 2012).

The diverted water is not consumed, but repeated diversions leave river segments with residual flow. Residual flows, weirs from the hydropower plants, gauging stations and other obstacles located along the river channel disrupt river connectivity and constitute a barrier for fish movement upstream and downstream. The river also receives the discharge from several urban and industrial wastewater treatment plants (WWTPs), especially at its lower course, where these anthropogenic activities mainly concentrate (Fig. 1a). The mining activity existing in one of the Llobregat tributaries is responsible for high salinity concentrations in the river. A brine collector transporting mining waste directly to the Mediterranean was built (Marcé *et al.* 2012). Finally, two drinking water treatment plants (drinking WTPs) are located close to the outlet.
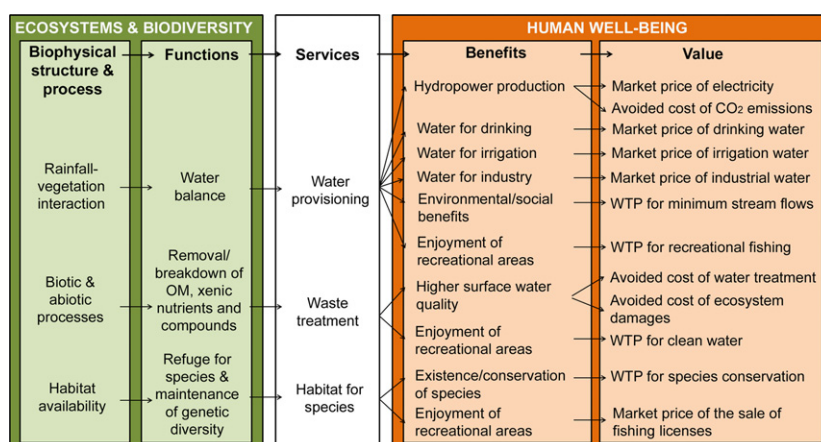
SELECTED MEASURES

Eighteen different types of measures were included by the regional water agency (the Catalan Water Agency) in the programme of measures for the Llobregat RBMP (ACA 2010a). Among those, we selected four types to perform the CEA and the CBA: implementation of environmental river flows (M1), improvement of river connectivity (M2), treatment of urban wastewater (M12) and reduction in saline pollution (M16). The rationale behind the selection of those four types of measures was to use some of the most commonly implemented management actions in Europe (EEA 2012), to show the usefulness of the proposed approach rather than to assess the impact of the implementation of all the programme of measures in that particular river basin. For each measure, we selected one or more actions depending on data
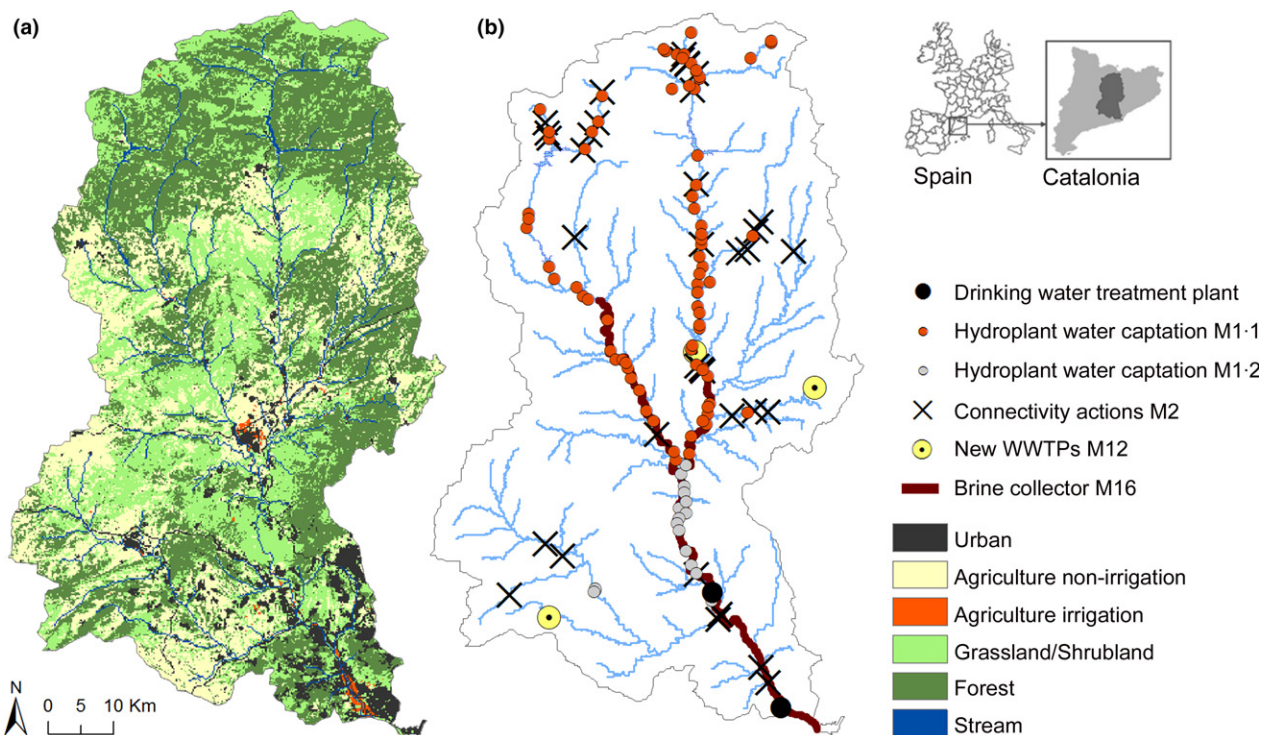
Fig. 1. Llobregat River basin land uses (a) and spatial locations of the selected measures to be implemented (b). WWTP stands for wastewater treatment plant. Measures: establishment of environmental river flows in the upper Llobregat and Cardener rivers (M1·1) and in the lower Llobregat and Anoia rivers (M1·2), improvement of river connectivity (M2), treatment of urban wastewater (M12), reduction in saline pollution (M16).

Table 1. Description of the actions selected in the Llobregat basin and expected effects in the model

Measure	Action	Description	Expected effect
M1 – Establishment of environmental river flows	M1·1	Establishment of environmental river flow rates in the upper Llobregat and Cardener rivers	Increase in water in the river and decrease in the apportionment for other uses
	M1·2	Establishment of environmental river flow rates in the lower Llobregat and Anoia rivers	
M2 – Improvement of river connectivity	M2	Improvement of river connectivity	Elimination/restoration of particular obstacles in the river channel priority reaches (weirs, gauge stations, etc.)
M12 – Treatment of urban wastewater	M12·1	New wastewater treatment plant with nutrient reduction in Mediona	Nutrient reduction efficiency objectives for the treatment of urban wastewater (RD 509/1996)
	M12·2	New wastewater treatment plant with nutrient reduction in Balsareny	
	M12·3	New wastewater treatment plant with nutrient reduction in Moià	
M16 – Reduction in saline pollution	M16·1	Reduction in saline pollution in the medium–low Llobregat basin	Attainment of the environmental objectives (for conductivity) for chemical and ecological status of surface water bodies (ACA 2010b)
	M16·2	Reduction in saline pollution in the medium–low Llobregat basin	
	M16·3	Minimization of the impact of salt mines	
	M16·4	Minimization of the impact of salt mines	

Fig. 2. Pathways from biophysical structures and processes to human well-being for three freshwater-related ecosystem services. WTP stands for willingness to pay.

availability regarding the expected effects of the action (Table 1). It is important to note that a single action can affect the provision of more than one ecosystem service and therefore it might accrue for multiple benefits. Although the efficacy of different actions varies when they are implemented individually or in combination with other actions, we analysed the effect of each action individually for the sake of simplicity.

MODELLING APPROACH

We followed the conceptual approach of The Economics of Ecosystems and Biodiversity (TEEB 2010), which describes the pathway from ecosystems and biodiversity to human well-being (Fig. 2) in order to assign the relevant benefits to each considered ecosystem service. This approach clearly differentiates among ecological phenomena (functions), their direct and indirect contribution to human well-being (services) and the gains they generate in well-being (benefits). Thus, benefits correspond to the gains in well-being from each of the three considered services potentially affected by the selected management actions (Fig. 2). To quantify the effects of the management actions on these benefits, we used two different models: AQUATOOL (Andreu, Capilla & Sanchis 1996) and InVEST (*Integrated Valuation of Ecosystem Services and Tradeoffs*) (Tallis *et al.* 2011), which can be complementary for issues that cannot be adequately assessed within a single model platform. AQUATOOL is a monthly Decision Support System Shell for integrated water resources management at the river basin scale, and we applied two of its modules: SIMGES and GESCAL. SIMGES is a simulation–optimization module based on a flow network algorithm that solves the water allocation of complex water resource systems with surface and groundwater storage, intake, transport, artificial recharge, use and consumption elements; GESCAL simulates the evolution of water quality in the river network. The water quality variables considered were temperature, dissolved oxygen, organic matter, nutrients and toxic pollutants, among others. InVEST is a spatially

explicit ecosystem service tool consisting of a suite of models available to estimate levels of different benefits at the annual scale. Information about data requirements and outputs of the models applied is listed in Table S1 in Supporting Information. Given the selection of services, we considered in our study as many benefits as possible as long as we could maintain the possibility of applying at least one valuation metric to calculate its annual monetary value.

EFFECT OF MANAGEMENT ACTIONS

The effect of management actions was calculated as the change in ecosystem status (subsequently integrated in a CEA) and the change in the provision of benefits from ecosystem services (subsequently integrated in a CBA).

Cost-effectiveness analysis

The effects of management actions on the ecological status of water bodies were estimated from the induced changes in threat levels. The relationship between ecosystem status and threat level was based on a study performed by the regional water agency, which related the current 13 main threats in the Llobregat basin to the current ecosystem status (ACA 2014). Specifically, this study assigned a value between 0 (no pressure) and 3 (high pressure) to each of the 13 identified threats for each water body. The threat values were based on the threat's magnitude, the water bodies' vulnerability and the environmental objective defined for each threat. Environmental objectives corresponded to values from which a perturbation on the ecosystem was expected to occur. Thus, when the effect of the threat equalled the environmental objective, the threat was assigned a value of 1 (i.e. the risk of not meeting the environmental objective was low). In contrast, when the effect of the threat exceeded the objective, a value of 2 or 3 was assigned (i.e. the risk of not meeting the environmental objective was higher). To estimate the total threat level for the scenario previous to the implementation of the management action, we aggregated the threat values of the individual threats for the whole river basin (Table S2). The effects of management actions were estimated by assigning a threat level of '0' to those threats directly affected by the specific management actions: the establishment of environmental river flows minimized the threats posed by water abstraction; the improvement of river connectivity affected the threats posed by dams and weirs; the treatment of urban wastewater minimized the threats posed by urban discharge; and the reduction in saline pollution minimized the threats posed by salinization. To sum up, the threat level after the implementation of the management actions was calculated after aggregating the values of individual threats for the whole river basin (Table S2). The effect of each management action in terms of ecosystem status was calculated as the difference between the total threat level before and after the implementation of the management action. Then, this change in ecosystem status was compared with the net present value of costs. The considered costs included the implementation costs and the exploitation and maintenance costs of management actions.

Cost–benefit analysis

The considered benefits are listed in Table S3, and the equations applied to calculate the monetary value of each benefit are described in Table S4. When the same benefit was assessed using more than one valuation metric, an average result is reported. For each of the selected management actions, the benefits expected to be affected by the action were calculated (1) with the implementation of the action and (2) without the implementation of the action. The marginal value of the action was calculated as (1–2), accounting for the change in benefit provision after implementation of the action. Calculations were performed at the sub-basin scale (sub-basins associated with each water body) and eventually aggregated to obtain a value for the whole basin. The obtained marginal values can be positive or negative; positive values mean that the implementation of the action increases gains in well-being (coherent to benefit gains in the economic analysis), whereas negative values imply the increase in well-being losses or 'dis-benefits' (TEEB 2010) (coherent to opportunity costs or benefit losses in the economic analysis).

The considered costs included the implementation costs, the exploitation and maintenance costs and the opportunity costs of foregone alternatives. Both marginal benefits and costs were expressed as net present values, calculated considering a period of 15 years and a discount rate of 5%. Fifteen years is a commonly selected period because it often corresponds to the useful life span of certain measures (i.e. those involving wastewater treatment plants, although other life spans have also been considered elsewhere according to plant-specific technology) (Del Saz-Salazar, Hernández-Sancho & Sala-Garrido 2009; Molinos-Senante, Hernández-Sancho & Sala-Garrido 2011). This timespan coincides approximately with the time frame for the implementation of the WFD (by 2027). The 5% discount rate was selected based on the recommendation of the European Commission of this value as an indicative benchmark for public investment projects (EC 2006). However, lower discount rates (2% and 3%) also have been tried in order to assess the sensitivity of the results to this parameter.

Results

COST-EFFECTIVENESS ANALYSIS

The management action providing the highest gain in ecosystem status at the river basin scale was the establishment of environmental river flows, followed by the management actions for the reduction in saline pollution and the improvement of river connectivity (Fig. 3a; see Table S5 for more detail). The ranking of management actions differed when considering the costs, as the management action with the best cost-effectiveness was one of the actions for the reduction in saline pollution (M16·3). After that, actions for the treatment of urban wastewater held the second position in terms of cost-effectiveness. The management action with the lowest cost-effectiveness was one of the actions for the reduction in salinity (M16·1), because it incurred a considerably higher cost than the other actions selected in this study.

EFFECTS OF MANAGEMENT ACTIONS ON BENEFITS

The management actions providing the highest gain in the benefits associated with the considered ecosystem services
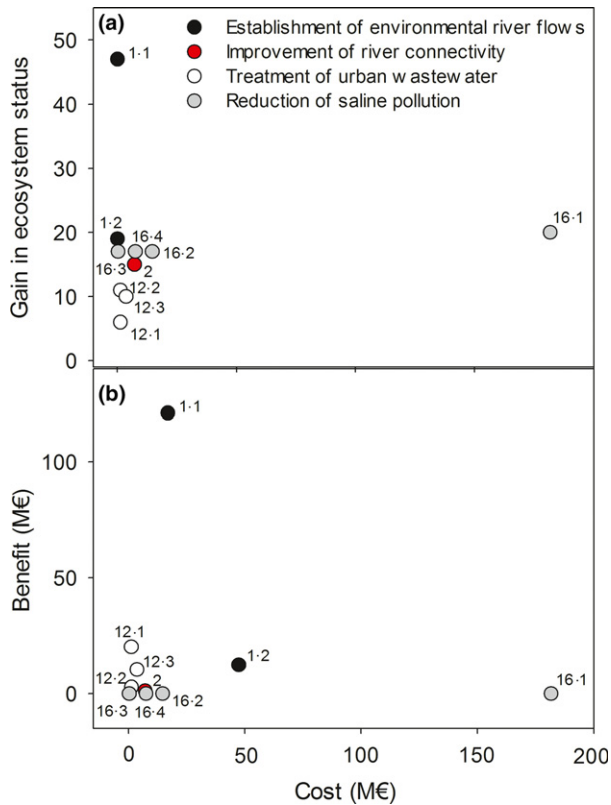
Fig. 3. Cost-effectiveness analysis (a) and cost–benefit analysis (b) of the selected actions of the programme of measures in the Llobregat River basin. Cost in (a) refers to the cost of implementation + the cost of exploitation and maintenance. Cost in (b) is the cost of implementation + the cost of exploitation and maintenance + the cost of opportunity.

Table 2. Annual marginal benefits after the implementation of the selected actions in the entire Llobregat basin. Positive values refer to benefit gains, and negative values to benefit losses

Action	Benefits/opportunity costs	Value ($€$ basin^{-1} year^{-1})
M1·1	Hydropower production	−1 173 088
	Water for drinking	−85 024
	Water for irrigation	−33 855
	Water for industry	−221 175
	Environmental/social benefits	5 334 487
	Existence/conservation of species diversity	97
	Enjoyment of recreational areas	5 468 681
M1·2	Hydropower production	−371 109
	Water for drinking	−3 857 581
	Water for irrigation	−2844
	Water for industry	0
	Existence/conservation of species diversity	752
	Enjoyment of recreational areas	1 097 904
M2	Existence/conservation of species diversity	109 461
	Enjoyment of recreational areas	0·4
M12·1	Higher surface water quality	23 404
	Enjoyment of recreational areas	1 773 261
M12·2	Higher surface water quality	37 968
	Enjoyment of recreational areas	209 566
M12·3	Higher surface water quality	102 709
	Enjoyment of recreational areas	819 933
M16·1	Higher surface water quality	0
M16·2	Higher surface water quality	0
M16·3	Higher surface water quality	0
M16·4	Higher surface water quality	0

were actions for the establishment of environmental river flows (M1·1 and M1·2) (Table 2). Actually, the establishment of environmental flows in the upper Llobregat basin (M1·1) caused both benefit gains and losses, which were estimated to amount to 10·8 M€ and −1·51 M€, respectively. The greatest losses were related to the hydropower production, followed by losses of water use by industry, drinking and irrigation. The highest gains were related to the enjoyment of recreational areas and environmental/social benefits. The assessment of hydropower production gave different economic estimations depending on the applied valuation metric (see Table S3 for a compilation of the applied metrics): a loss value of −2·3 M€ year^{-1} was obtained using the market price of electricity, whereas −0·048 M€ year^{-1} was obtained when the avoided cost of CO_2 emissions was used instead. This difference is highly relevant and demonstrates that a different result is obtained according to the valuation metrics applied in the calculation of the benefit. To reduce the overall uncertainty of results, the average value obtained with the different valuation metrics is reported in Table 2. Similarly, two different values were estimated for the enjoyment of recreational areas, one through contingent valuation and the other through the market price, and an average value

of 5·46 M€ is reported in Table 2. The same benefits assessed for the establishment of environmental flows in the upper basin were also assessed in the lower basin (M1·2), except for environmental/social benefits, for which we lacked appropriate data since the lower Llobregat basin receives much higher urban and industrial pressures. The total annual gains and losses estimated by the implementation of environmental river flows in the lower Llobregat basin amounted to 1·1 M€ and −4·2 M€, respectively. The highest losses corresponded to water for drinking, followed by hydropower production, water for irrigation and water for industry, whereas the highest gains corresponded to enjoyment of recreational areas. Unlike in the upper basin, the market price of fishing licences was not calculated in the lower basin because this metric was only applied to river reaches with trout fishing, which are only present in the upper part.

The management action for the improvement of river connectivity (M2) caused total annual gains estimated to amount to 0·1 M€ for the whole basin. The highest gains were obtained for existence/conservation of species diversity. Actions for the treatment of urban wastewater (M12·1 to M12·3) were responsible for total estimated annual gains of 1·8 M€, 0·25 M€ and 0·9 M€, respectively. The highest gains were obtained for the enjoyment

of recreational areas, followed by improvement in surface water quality. Improvement in water quality was valued both through the avoided cost of the treatment of water for drinking and through the avoided cost of ecosystem damages (see average in Table 2). In this case, the value of the avoided cost of drinking water treatment was zero because before the application of the measure the average annual concentrations of nutrients and organic matter at the two drinking WTPs were already below the legal threshold for drinking water (80/778/CEE and 98/83/EC). Thus, no further treatment was needed to reduce the concentration of nutrients and organic matter to meet legal specifications. Conversely, the valuation of the improvement of water quality through the avoided cost of ecosystem damages reported gains because nitrogen concentrations considered to have effects on ecosystems (which are not regulated) were exceeded in some water bodies affected by this management action. Thus, nitrogen reduction in these water bodies was needed in order to protect the quality of the ecosystem. We could only assess

one benefit affected by actions for the reduction in saline pollution (M16·1 to M16·4). The benefit corresponded to a gain through the avoided cost of treating water for drinking purposes. In all cases, the annual gains were 0 € because the average annual conductivity at the two drinking WTPs already fulfilled the legal threshold before the application of the management actions, and therefore, no further salinity reduction was needed.

SPATIAL DISTRIBUTION OF MARGINAL BENEFITS

The variation of benefits resulting from the application of actions was heterogeneously distributed across the basin. Figure 4 displays the marginal benefit gains (in blue) and losses (in red) after the establishment of environmental flows in the upper Llobregat (M1·1). The spatial distribution of marginal benefits affected by the other actions is detailed in Figs S1–S3. For all the benefits derived from action M1·1, the sub-basins in the lower Llobregat basin received zero marginal value because this action affected
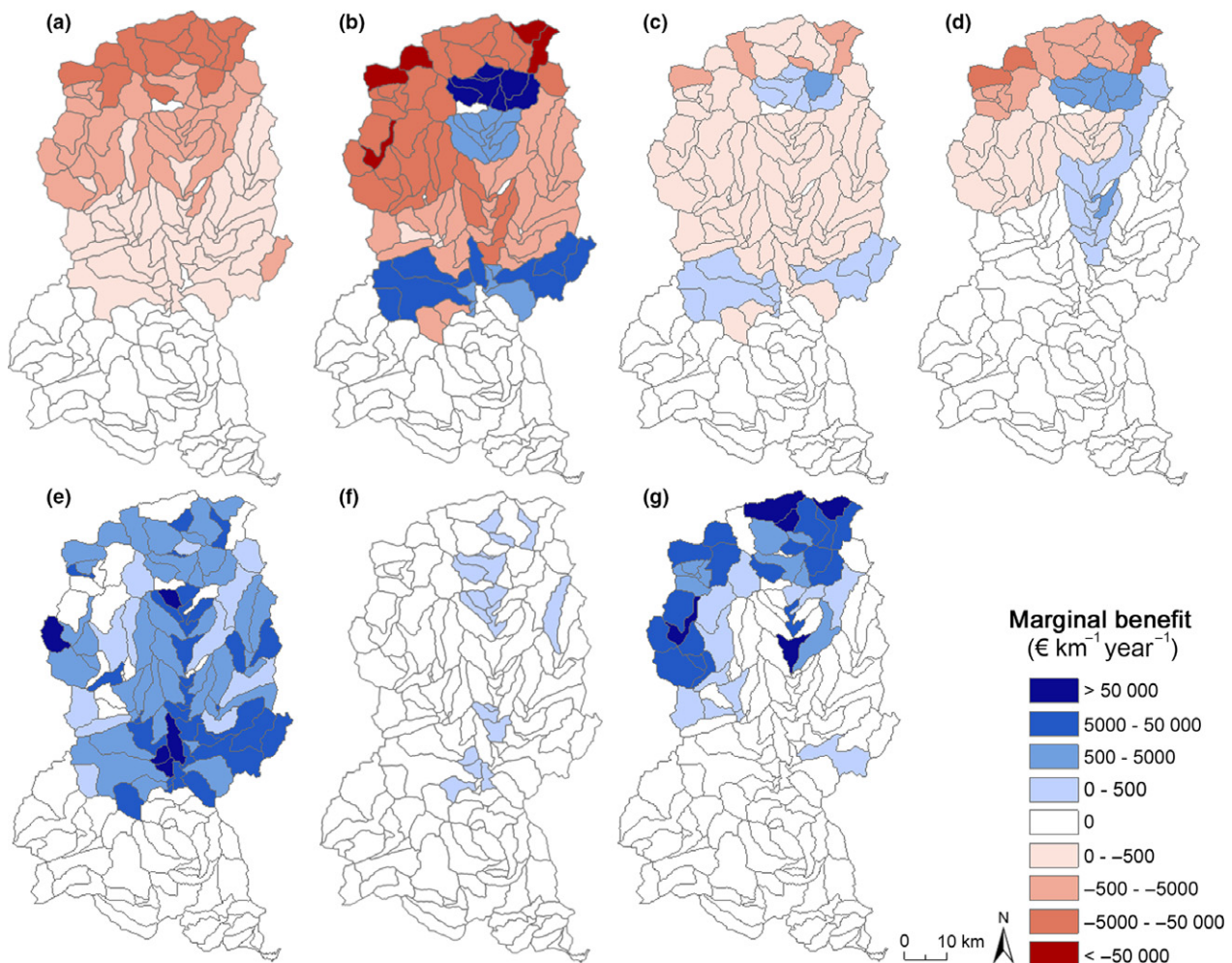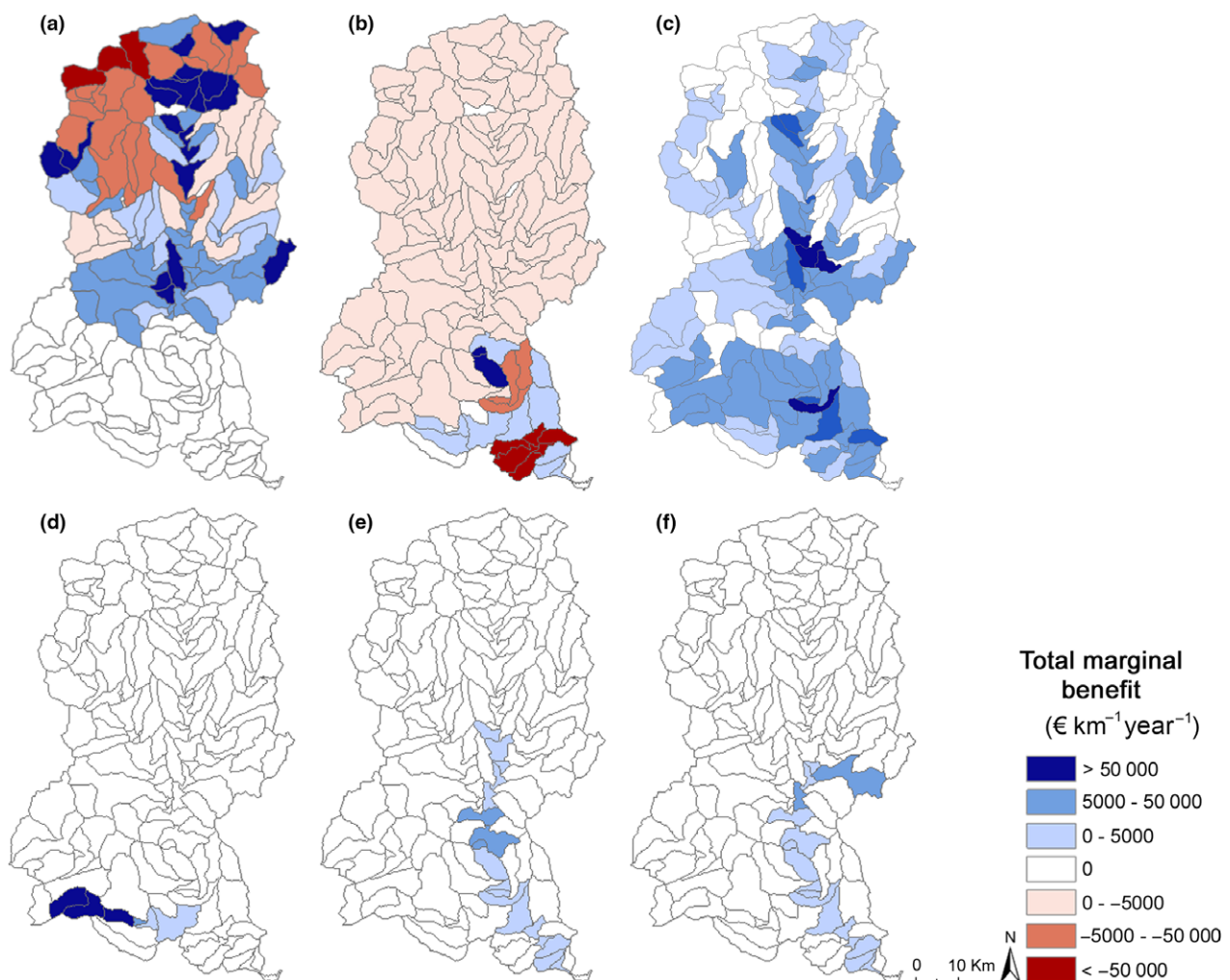

Fig. 4. Effects of the establishment of environmental river flows in the upper Llobregat basin on the potential benefits for hydropower production (a), water for drinking (b), water for irrigation (c), water for industry (d), environmental/social benefits (e), existence/conservation of species diversity (f) and enjoyment of recreational areas (g). Results are expressed as marginal values in € per kilometre of river per year.

only the upper Llobregat River. Hydropower production was the only category with losses in all the sub-basins affected by the action (Fig. 4a). Losses were greater in headwaters and decreased downstream. When regarded at the sub-basin scale, water for drinking, irrigation and industry showed gains or losses depending on the region of the basin (Fig. 4b–d). The highest losses in all cases continued to be associated with the upper part of the basin, whereas gains were associated with areas downstream of those water bodies with implemented environmental flows and upstream of water demand intakes. This finding is related to the water resource production pattern and the defined water management strategy in the model, which aims to satisfy multiple objectives of supply to the various demands. The benefit categories experiencing gains presented a substantially different spatial distribution (Fig. 4e–g). Environmental/social benefits tended to be greater in areas of greater population concentration, benefits to the existence/conservation of species diversity

were inversely related to the sites of water abstraction, and enjoyment of recreational areas had higher benefit values in headwaters, where the main water sources were found.

TOTAL MARGINAL BENEFITS OF ACTIONS

When the marginal values of all the benefits assessed for a particular action were aggregated, a map of the total marginal benefit of the action was obtained, corresponding to a change in the partial total economic value of the basin (Fig. 5). The upper part of the basin experienced the greatest total losses after the establishment of environmental river flows, whereas total gains were more heterogeneously distributed (Fig. 5a). The establishment of environmental river flows in the lower Llobregat basin resulted in net losses in the upper Llobregat (Fig. 5b), even though the action was only implemented in the lower part of the river. This effect occurred because for one of

Fig. 5. Total marginal benefit after the implementation of the selected actions in the Llobregat River basin: establishment of environmental river flows in the upper Llobregat basin (a), establishment of environmental river flows in the lower Llobregat basin (b), improvement of river connectivity (c), treatment of urban wastewater in Mediona (d), treatment of urban wastewater in Balsareny (e) and treatment of urban wastewater in Moià (f). Results are expressed as marginal values in € per kilometre of river per year.

the assessed benefits (hydropower production), all sub-basins located upstream from the water demand intakes (hydropower plants) were affected and received a marginal value, which in this case corresponded to a loss of hydropower production. This connectivity between upstream and downstream areas did not apply in the case of the other benefits assessed for the establishment of environmental river flows in the lower basin (Fig. S1). The improvement of river connectivity got the greatest total gains in the middle part of the basin and downstream, where a larger population was concentrated (Fig. 5c). Actions for the treatment of urban wastewater resulted in net gains downstream from their implementation, that is downstream of the new WWTPs (Fig. 5d–f).

COST–BENEFIT ANALYSIS

The action with the highest net balance (difference between the net present value of benefits and costs) was the establishment of environmental river flows in the upper Llobregat basin (see Table S6 for more detail) (Fig. 3b). Management actions for the treatment of urban wastewater also returned a positive net balance, with action M12·1 resulting in the highest value gain. All other management actions had a negative net balance, as costs were greater than the estimated benefits. The ranking slightly changed when analysing the benefit-to-cost ratio, as the action resulting in the highest benefit-to-cost ratio was the treatment of urban wastewater from action M12·1, followed by the establishment of environmental river flows in the upper basin, and the treatment of urban wastewater at the two other WWTPs (M12·2 and M12·3) (Fig. 3b). Actions for the establishment of environmental river flows in the lower Llobregat basin and the improvement of river connectivity resulted in a small benefit-to-cost ratio, and the benefit-to-cost ratio was zero for all actions devoted to the reduction in saline pollution because calculated benefits were zero in that case. The use of lower discount rates (2% and 3%) increased the benefits obtained for management actions more than the costs, although changes were not high (around 10% for benefits and around 4% for costs). Consequently, some actions received a different benefit-to-cost ratio, even though observed trends in the CBA remained the same.

Discussion

The ecosystem services approach presented here allows for a spatially explicit quantification of the marginal benefits of management actions proposed by river authorities in the programme of measures of RBMPs. Management actions identified as the most cost-effective in the CEA differed sometimes from those receiving the best benefit-to-cost ratio according to the CBA, stressing that gains in ecosystem status do not necessarily involve gains in benefits derived from ecosystem services, or at least not those quantified here. Overall, CBA proved to be complementary to the CEA, and the integration of ecosystem services in the implementation of river basin management plans is therefore proposed to move from a single- to a multiobjective decision-making approach in the design and prioritization of management actions.

CONSIDERATIONS ABOUT THE APPROACH

Caution should be taken when analysing the results of the performed assessment of CBA for a series of management actions, as in our study only four types of management actions were considered, and not all the ecosystem services but a subset of them were included in the analysis. As a result, the estimates of environmental benefits have an associated uncertainty often combined with a lack of information that might compromise the informative capacity of the applied tools. Our assessment was performed considering a best-guess range of benefits based on a compilation of past cases and scientific literature that certainly excludes many potentially influenced benefits that may be important, among these the lack of a valuation technique converting benefits to a monetary value, or the impossibility of assessing ecosystem functions that entrain relevant services with the models applied in the context of the study. For example, the effect of the reduction in saline pollution on the enjoyment of recreational areas of the Llobregat basin (i.e. angling) could not be assessed because of the inability to find a relationship between individual willingness to pay and improvement in water quality caused by a reduction in water salinity. Similarly, the effect of the treatment of urban wastewater on the existence/conservation of species diversity was not quantified because of the limitations of the applied habitat quality model, which was not sensitive enough to small changes in wastewater treatment plant performance. However, the inability to estimate some benefits in our work does not prevent their assessment in other case studies that do not show such limitations. Additional uncertainty can also be introduced in the analysis through the application of benefit transfer (i.e. to value environmental/social benefits derived from the establishment of environmental river flows), as this technique uses data obtained from other sites (Plummer 2009). Regardless of the constraints in the modelling approach, we should be aware that the value of the parameters used to assess the different benefits can also highly influence the outcome of CBA, and for this reason, the use of a range of possible values is preferred to account for uncertainty (Boithias *et al.* 2016). Likewise, caution should be taken when analysing CEA results, as the expected changes in ecosystem status of management actions are not based on models comparing the changes in the threat level to changes in the ecosystem status of water bodies. Instead, we applied an approach in which the threat directly affected by the management action was set to zero after the application of the action. Establishing this type of relationship would require a notable amount of work and was beyond the scope of our study.

COST-EFFECTIVENESS AND COST–BENEFIT ANALYSES
IN THE LLOBREGAT CASE STUDY

The performed CBA and CEA indicate that the establishment of environmental river flows in the upper Llobregat River was the management action that maximizes the balance between the marginal increase in ecosystem services and the ecosystem status in the basin. The management actions for the treatment of urban wastewater were also identified as win–win, since they yield a positive balance for both ecosystem services and ecosystem status in the basin. However, the increase in ecosystem status was lower than that obtained with all the other selected management actions. This is because the actions for the treatment of urban wastewater are more locally focused; only involving particular wastewater treatment plants. When environmental river flows were implemented in the lower Llobregat River, the expected gain in ecosystem status was much lower than that obtained in the upper basin, and there was a marginal decrease in ecosystem services. The same happened with the management action for the improvement of river connectivity. In regard to the management actions for the reduction in saline pollution, they did not yield net gains for ecosystem services according to the assessed benefits, but were expected to result in ecological gains at the basin scale. The mismatch between gains in ecosystem status and human well-being was not an unexpected result, as other studies have stressed that the delivery of ecosystem services is not necessarily related to species richness (Adams 2014; Winfree *et al.* 2015). A clear example of this mismatch in the Llobregat is exemplified by dams and weirs, which certainly favour the benefits associated with hydropower production (Terrado *et al.* 2014), but constitute a threat to freshwater habitat quality (Terrado *et al.* 2016).

The results obtained from the CBA revealed the importance of considering opportunity costs together with benefits in the decision-making process, as opportunity costs for the assessed actions can range from 0% to 100% of the total costs. Those of 0% corresponded to measures for which no cost of opportunity could be assessed. Those of 100% corresponded to measures with no implementation and exploitation/maintenance costs, or to those with implementation costs conceived as compensation to beneficiaries potentially negatively affected by the measure. One of these latter cases would be the establishment of environmental river flows, where negatively affected beneficiaries would be hydropower plants, farmers, industries, etc. Efficiency gains from including opportunity costs (not fully taken into account in a CEA) in the process of environmental planning have already been demonstrated in previous studies (Naidoo *et al.* 2006; Adams, Pressey & Naidoo 2010).

INTEGRATION OF ECOSYSTEM SERVICES IN RIVER
BASIN MANAGEMENT PLANS

The proposed assessment approach of the marginal benefits resulting from management actions in river basins can be used in CBA to identify the trade-offs among multiple benefits affected by different actions. More importantly, the CBA proved to be complementary to the CEA, and the integration of ecosystem services in the river basin management plans is therefore proposed to move from a single- to a multiobjective decision-making approach in the design and prioritization of management actions. In fact, this methodological approach addresses better multibenefit goals, allowing the identification of win–win management actions that maximize simultaneously ecosystem status and human well-being. The approach makes a contribution to already available management approaches and helps policymakers to gain insights and evaluate policy impacts comprehensively.

In summary, we provide a flexible and systematic framework to assess the effect of management actions proposed in the programme of measures for the fulfilment of the WFD objectives (see Table S4 for a list of ready-to-use equations) that can be easily extended to the valuation of other benefits and services and adapted to other river basins. The implementation of the ecosystem service concept into existing frameworks such as the WFD and its consideration through CBA allows for the accounting of trade-offs among different management actions. However, although ecosystem services are obviously a strategic tool for conservation, caution should be taken in creating schemes based exclusively on the value of ecosystem services, since they may not parallel gains in ecosystem status. To prevent such an outcome, our approach is based on a combination of CEA and CBA, therefore allowing the selection of optimal management actions simultaneously maximizing the value of ecosystem services and the gains in ecosystem status of river basins. Although win–win outcomes may not always be possible in practice, adding a systematic basis to decision support that addresses interdependencies between human well-being and ecosystem status provides transparency and a more inclusive basis for decision-making.

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Data accessibility

Threat level in the basin: ACA (2014).

Benefit definition, equations and parameter values: uploaded as online Supporting Information (Tables S3 and S4).

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Supporting Information

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

Fig. S1. Effect of the establishment of environmental flows in the lower basin on the considered benefits.

Fig. S2. Effect of the improvement of river connectivity on the considered benefits.

Fig. S3. Effects of the treatment of urban wastewater on the considered benefits.

Table S1. Data requirements and outputs of the models applied.

Table S2. Threat level in the Llobregat basin before and after the application of the management actions.

Table S3. Benefits, beneficiaries and valuation of the management actions.

Table S4. Equations and parameters used for benefit valuation.

Table S5. Costs of the management actions and predicted gain in ecosystem status.

Table S6. Costs and benefits of the management actions.