Placing ecosystem services at the heart of urban water systems management

X. García a,b, D. Barceló a,c, J. Comas a,d, Ll. Corominas a, A. Hadjimichael d, T.J. Page e,f, V. Acuña a,*

a Catalan Institute for Water Research (ICRA), Carrer Emili Grahit 101, 17003 Girona, Spain
b International University of Catalonia, Carrer Immaculada 22, 08017 Barcelona, Spain
c Department of Environmental Chemistry, Institute of Environmental Assessment and Water Research (IDAEA-CSIC), Carrer Jordi Girona 18-26, 08034 Barcelona, Spain
d Laboratory of Chemical and Environmental Engineering (LEQUIA), Institute of the Environment, Universitat de Girona, Campus Montilivi s/n, 17071 Girona, Spain
*e Australian Rivers Institute, Griffith University, Nathan, 4111 Queensland, Australia
f International University of Catalonia, Carrer Emili Grahit 101, 17003 Girona, Spain

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A B S T R A C T

Current approaches have failed to deliver a truly integrated management of the different elements of the urban water system, such as freshwater ecosystems, drinking water treatment plants, distribution networks, sewer systems, and wastewater treatment plants. Because the different parts of urban water have not been well integrated, poor decisions have been made for society in general, leading to the misuse of water resources, the degradation of freshwater ecosystems, and increased overall treatment costs. Some attempts to solve environmental issues have adopted the ecosystem services concept in a more integrated approach, however this has rarely strayed far away from pure policy, and has made little impact in on-the-ground operational matters. Here, we present an improved decision-making framework to integrate the management of urban water systems. This framework uses the ecosystem service concept in a practical way to make a better use of both financial and water resources, while continuing to preserve the environment.

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1. Introduction

The urban water system (UWS) is the total sum of the natural and human-engineered parts of the water cycle in urban areas. It includes both the existing natural, freshwater ecosystems, and the water infrastructure that we have built to supply us with drinking water and to collect, move and treat our wastewater. Basically, this constructed infrastructure includes drinking water and wastewater treatment plants, distribution and sewer networks. All of these elements of the UWS are intrinsically linked by the movement of water, as well as any associated matter and energy fluxes, leading to a unique and vital socio-environmental system. Because of the obviously connected nature of the different parts of the system, management actions on any component will influence the others in a cascading effect, with potentially negative or unpredictable outcomes. Therefore, it is very important to push forward the integrated management of the whole system to make more effective and beneficial decisions for both the economy and environment (Everard, 2014; Olander et al., 2015; Xue et al., 2015).

Unfortunately, despite the intimate relationship between each part of the system, different pieces of legislation tend to regulate each element individually. This leads to a separate “tunnel-vision” management of each element of this socio-environmental system rather than as a whole (Kiparsky et al., 2013). For example, in the European Union there are a series of directives dealing with the different parts rather than the entire UWS, such as Directive 98/83/EC for drinking water, 91/271/EC for wastewater, and 2006/7/EC for bathing waters. This has led to isolated, fragmented management of each element, responding to specific legislation, and has meant poor decision-making across the system as a whole, often resulting in the degradation of freshwater ecosystems (Corominas et al., 2013; Richter et al., 2003). Because of these often negative feedbacks between the different elements of the UWS, there is a growing interest in integrated management. In fact, several studies have claimed to have integrated management of UWS (Bixio et al., 2006; Lazarova et al., 2001), but the success of these schemes has been limited, and sometimes controversial (Hering and Ingold, 2012; Van de Meene et al., 2011). One reason these have fallen down is because management actions have only considered those costs and benefits directly tied to water, such as wastewater treatment or some ecosystem services with a market value like water supply for agriculture (Hering and Ingold, 2012); thus ignoring the effects on other ecosystem services and natural capital.
Ecosystem services can actually be used as a way to assess the different costs and benefits over the whole UWS related to a particular management action on one (or more than one) of the UWS elements. If we consider ecosystem services in our management decisions, it allows us to link the different parts of the system over both space and time, and to account for other benefits and costs to society beyond those just directly associated with water. This means that the consideration of the different costs and benefits related with the UWS management might allow for the identification of optimal solutions from a socio-economic and environmental point of view (Terrado et al., 2016); usually after performing trade-off analysis with multiple ecosystem services and multiple stakeholders, such as the general public, businesses and ecological assets. Furthermore, the use of ecosystem services in water management might support managers in communicating key issues and engaging people (Everal, 2012; Olander et al., 2015). However, the usage of ecosystem services in UWS management has been hampered because of the efforts and costs associated with the detailed assessments of ecosystem services, as those require huge amount of data and the need to include more people and organizations (Hering et al., 2014). Even contexts that include some ecosystem services, often do not account for all relevant ecosystem services, particularly those with non-use values (such as cultural, educational, spiritual, or existence values) (Griffths et al., 2012).

In sharp contrast with the rare use of ecosystem services in UWS management, there has been a lot of research and many policy initiatives to foster the use of ecosystem services in environmental management more generally, some of which are focused on water. For example, the Water Framework Directive (Council of the European Communities, 2000), the “Roadmap to a Resource Efficient Europe” (European Commission, 2012a), and the “Blueprint to Safeguard Europe’s Water Resources” (European Commission, 2012b) all this within the EU. Across Europe, new conservation policy will require incorporating ecosystem services into policy-making (Maes et al., 2012), which justifies their use in UWS management. This trend is also evident in the US, where numerous federal agencies have begun to incorporate ecosystem services into land use planning, water resources management, and preparations for responding to climate change (Olander et al., 2015; Schaefer et al., 2015); most notably the environmental markets related to wetland mitigation banking and nutrient trading (Schaefer et al., 2015). While these initiatives are a start, they are fairly general in nature and lack concrete details of how exactly to apply the ecosystem services framework to real-world issues (Cook and Spray, 2012), in particular with the UWS. Furthermore, they lack standards that clearly define the terminology of ecosystem services, and acceptable data and methods (Polasky et al., 2015). There have been some attempts to clarify the situation, such as the South African National Water Act (Republic of South Africa, 1998) and “European Innovation Partnership on Water” (European Commission, 2012). The latter has an action group working out how to equate healthy ecosystems with cash amounts. Similarly, a recent study indicates that a truly societal transformation towards sustainable water management requires primarily the estimation of impacts and reduction of pressures on the water ecosystems (Knieper and Pahl-Wostl, 2016). There is definitely a growing general interest in using ecosystem services in UWS management, but we are still a long way from achieving our goal of practical integration of the ecosystem services into the management of UWS.

Given this background, we describe a decision-making framework for the effective, integrated management of the UWS, considering all elements of the UWS and all costs and benefits of the ecosystem services influenced by the UWS management. To set the basis of the proposed framework, we first review and analyze the published scientific literature on using ecosystem services in water management.

2. Review and analysis of the research literature

The number of publications considering ecosystem services has boomed during the last decade, with around 29,210 papers to date (7974 of them since 2015) (Web of Science publications database, search term “ecosystem services”, on Apr. 25th 2016). Among those publications, 17,239 also deal with decision making and management (1792 of them since 2015) (”ecosystem services” AND “decision-making” OR “management” OR “cost benefit” OR “benefit cost”). Despite the skyrocketing number of publications on ecosystem services, which increased by almost 30% during the last 16 months, there are few examples on their use to support management of UWS, as we have only identified 46 publications specifically dealing with ecosystem services and management of the UWS (see complete list at SI). However, these publications illustrate the some of the multiple benefits that the consideration of ecosystem services in the UWS management might have, with examples spanning from the assessment of the impact of the urban river water quality improvement on human well-being to justify the required investment (Bateman et al., 2006), or the assessment of the benefits of watershed restoration on drinking water treatment plants (Honey-Roses et al., 2013) (Table 1). Regardless of the study goal and of the used decision-support tool, an important common factor among these publications is that the solution arrived at was different when ecosystem services were considered. More specifically, the management decisions would have been decided environmentally unfriendly, favoring inaction, had their cost-benefit analyses not included ecosystem services (Becker and Friedler, 2013; Halaburka et al., 2013; Martínez-Paz et al., 2014) (Table 1).

Overall, if we are to address complex interconnections between UWS elements and identify effective solutions in the management of UWS, we need to consider all elements, and the benefits and costs of all ecosystem services influenced by the management of the UWS. In fact, the benefits illustrated in these examples would have been probably more relevant if more UWS elements and ecosystem services were considered, as most publications included a low number of both (Fig. 1). Thus, clear patterns emerge if analyzing these publications by the considered UWS elements, ecosystem services and decision-support tool. In regards to the considered elements, more than 85% of the publications included freshwater ecosystems, and either an element related with water sanitation and/or with water supply, thus relating 2 (in 52% of the publications) or 3 (in 11% of the publications) elements (Fig. 1a). In regards to ecosystem services, 24% of the publications considered only 1 ecosystem service, and only 24% considered 5 or more ecosystem services. The most commonly considered ecosystem services were recreation and waste treatment (50 and 41%, respectively), followed by water provisioning and habitat or supporting service (both 37%) (Fig. 1b). Each case study was highly dependent on site-specific factors, like climate, technologies and history. Because of this, the ecosystem service chosen in each case was quite ad-hoc. This is because the type of ecosystem service selected was largely dependent on how it was valued, which, in turn, was largely determined by the objectives of that particular assessment and/or its specific time and economic constraints. Overall, the low number of services and elements of the UWS considered in current scientific literature indicate that we are far from achieving the integrated management of the UWS elements, and that ecosystem services are not commonly considered to quantify the complex interactions between UWS elements.

In regards to the considered decision-support tools, 39% of the publications did not consider any decision-support tool (Fig. 1c). Most of those were based on estimates of the marginal values associated with specific management actions, such as restoring or rehabilitating freshwater ecosystems (Bateman et al., 2006; Poor et al., 2007), upgrading wastewater treatment plants (Becker and Friedler, 2013; Verlicchi et al., 2012), constructing wetlands for wastewater treatment, and various other services (Dimuro et al., 2014; Yang et al., 2008) (Fig. 1c). Other publications assessed the added benefit of providing water of different
qualities, such as reclaimed effluent, for various uses, mostly agricultural or environmental (Kandulu et al., 2014; Menegaki et al., 2007; Molinos-Senante et al., 2011) (Table 1). The most commonly used decision-support tools were cost-benefit analysis (CBA) and financial analysis (FA) (23%) (Alam, 2008; Dimuro et al., 2014; Kandulu et al., 2014; Terrado et al., 2016), although cost-effectiveness analysis (CEA) (Gren, 1995; Terrado et al., 2016) and a multi-criteria analysis (MCA) (Bryan and Kandulu, 2011; Liu et al., 2013) were also occasionally used (Fig. 1c). Briefly, CBA is a rational and systematic approach used in public or private decision-making to evaluate whether the benefits (economic, environmental and social) of an action outweigh the costs; CEA is aimed at identifying the least-cost action or measure to achieve a predefined environmental objective, and therefore does not require the estimation of the benefits associated to ecosystem services; FA provides the decision maker with predictions of the expected future cash flows of the project and, in combination with the appropriate uncertainty analysis, assesses the risks associated with cash flows (Dayananda, 2002); and MCA is a discipline of operational research used to evaluate competing alternatives in cases where the decision maker needs to take several types of objectives (economic, environmental, social, technical, legal) into account without necessarily having to aggregate them into a single indicator (Vincke, 1992). This review and analysis of the existing literature points out the need for an structured and systematic framework to support the implementation of the ecosystem services concepts and tools to step forward for an integrated UWS management.

### 3. A proposal for a decision-making framework

We propose a framework of four key steps to integrate ecosystem services into the UWS management. These steps are: (i) Definition of goals and stakeholder involvement; (ii) Selection of socio-environmental metrics; (iii) Modeling to quantify performance criteria; and finally, (iv) application of the decision-support tool (Fig. 2).

#### 3.1. Definition of goals and stakeholder involvement

Step 1 is a stakeholder-driven process to define the goals of the management action/s (see examples of actions in Fig. 3). An extensive stakeholder engagement process should be set up to that involves scoping objectives, gathering information, and securing feedback through UWS planning advisory committees, composed of local representatives from diverse sectors and interests (whenever possible with representatives from the engineering and the environmental sectors), public consultations, and expert reviews. Bringing stakeholders in from the start of a process is better for overall engagement (Emerson and Nabatchi, 2015). The goal should reflect an improvement of the services provided

### Table 1

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Illustrative study</th>
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<tr>
<td>Improving the water quality in the river provides valuables ecosystem services to society (Bateman et al., 2006); Improving the water quality in the watershed influences significantly in the real estate prices (implicit price) (Poor et al., 2007).</td>
<td>Revealing water quality effects on human well-being</td>
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<tr>
<td>Provisioning reclaimed water for irrigation is a feasible alternative (Menegaki et al., 2007).</td>
<td>Revealing benefits of ecosystem restoration and/or conservation on human well-being</td>
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<tr>
<td>Improving the water quality in urban lakes influences significantly in the real estate prices (implicit price) (Gibbs and Halstead, 2002).</td>
<td>Revealing water quality and ecological restoration of urban rivers provide multiple ecosystem services to society (Looms et al., 2000).</td>
</tr>
<tr>
<td>Provisioning reclaimed water for industrial uses is a feasible alternative (Nahman and De Lange, 2012).</td>
<td>Including ecosystem services concept to compare various urban floodplain restoration plans helps to improve evaluation of possible trade-offs and optimize the strategies (Sanon et al., 2012).</td>
</tr>
<tr>
<td>Improving the water quality in both inland and coastal waters provides multiple benefits to society (Vesterinen et al., 2010).</td>
<td>Water quality and ecological restoration of urban rivers provide multiple ecosystem services to society (Halaburka et al., 2013).</td>
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<td>Including ecosystem services concept to compare various urban floodplain restoration plans helps to improve evaluation of possible trade-offs and optimize the strategies (Sanon et al., 2012).</td>
<td>Reusing reclaimed water for irrigation and environmental purposes provide multiple benefits to society despite allocation costs (Becker and Friedler, 2013).</td>
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<td>Water quality and ecological restoration of urban rivers provide multiple ecosystem services to society (Alam, 2008).</td>
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<td>Reusing reclaimed water for urban and environmental purposes provide multiple benefits to society (Verlicchi et al., 2012).</td>
<td>Stream flow augmentation using reclaimed water and urban river rehabilitation provide multiple and benefits to society (Martinez-Paz et al., 2014).</td>
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<tr>
<td>Including ecosystem services criteria in industrial water management measures evaluation demonstrate feasibility of green infrastructure (Dimuro et al., 2014).</td>
<td>Revealing water quality and constructed ecosystem effects on human well-being</td>
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<td>Including ecosystem services concept to compare various urban floodplain restoration plans helps to improve evaluation of possible trade-offs and optimize the strategies (Corominas et al., 2013).</td>
<td>Revealing relevance of management of individual elements on other UWS elements</td>
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<td>Including ecosystem services impact in urban wastewater system management scenarios evolution favors cost-efficient decisions (Corominas et al., 2013).</td>
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<td>Including ecosystem services concept in Water Framework Directive series of management actions help to consider their effect on social welfare (Terrado et al., 2016).</td>
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<tr>
<td>Including ecosystem services criteria to compare a mix and sequence of policy instruments (or policy designs) to address agricultural non-point source pollution helps to select the most optimal option (Bryan and Kandulu, 2011).</td>
<td>Including ecosystem services criteria in urban wastewater system management scenarios evaluation demonstrate feasibility of green infrastructure (Gren, 1995).</td>
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<td>Including ecosystem services concept on groundwater management helps to intertwine human and biophysical systems and understand complex governance regimes (Knipple and Pahl-Wostl, 2011).</td>
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<td>Including ecosystem services concept to compare various plans on biosphere reserve areas helps to improve evaluation of possible trade-offs and optimize the strategies (Onandia et al., 2013).</td>
<td>Complementing ecosystem services to the technological change is a cost-efficient approach (Honey-Roses et al., 2014).</td>
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by the UWS elements. The achievement of that goal might imply one or several actions which can target one or multiple UWS elements. After defining the different actions to be considered, data is gathered to create a baseline which is going to be used to compare the change induced by the different actions.

### 3.2. Selection of socio-environmental metrics

The selection of socio-environmental metrics includes the establishment of engineering and environmental performance criteria. In the engineering domain, performance criteria have to be defined to ensure the technical feasibility of the action, which could include, for example, reliability of water supply, reliability of wastewater treatment and costs of implementation of the measures. Environmental performance metrics are also identified to represent desirable ecosystem services, which will normally fall in the accounting of benefits of the implementation of the management actions (which will sum-up on top of the technological benefits). Such performance criteria include provisioning, regulating, habitat, and cultural & amenity services (de Groot et al., 2010). At this step, it is still critical to engage representatives of the involved stakeholders through participative processes to discuss and refine objectives, measure acceptability of management actions, assess their data availability and further define potential links between actions on the UWS elements and ecosystem services. Plainly, this should also polish the discussion and selection of the most relevant ecosystem services to include in the assessment, as well as the spatial and temporal scales to adopt in the study (Turner and Daily, 2008). The development of a conceptual diagram (Fig. 3) can often provide important insights for decision-making, as it can identify the full range of pathways through which management actions on the UWS can influence human well-being (Olander et al., 2015).

Whereas some linkages between the management actions on the UWS elements and the ecosystem services affected can be obvious, other ones can be addressed by using a classic risk-assessment approach (Arkema et al., 2014) to identify, for instance, the UWS management action that pose the greatest threat to the habitats that deliver these ecosystem services. Common examples of the close link between UWS elements and ecosystem services include the improvement of the recreational or habitat services after upgrading the wastewater treatment systems (Garcia et al., 2016), as well as improving the ecosystem service of water purification by introducing restoration measures that eventually enhance security in water supply (Acuña et al., 2013). Full consideration also needs to be made for those actions in one UWS element which negatively affect the performance of another one. This is because a complex web of both positive and negative socio-economic and environmental impacts can arise from even a single decision focusing on a sole element but that can influence other UWS elements through different linkages. For instance, the consideration of ecosystem services in their assessment criteria of an aquatic vegetation removal plan for flood risk mitigation, allowed the identification of significant trade-offs by limiting the denitrification capacity of the river ecosystem as...
well as its surface water levels, entailing direct costs to the water supply utilities (Boerema et al., 2014).

3.3. Socio-environmental modeling

This step involves the modeling of the system to be able to assess any impact of a given management action on the socio-environmental system (Vlachopoulou et al., 2014). Models range from simple mathematical operations to complex algorithms implemented in software packages. Models allow us to describe how a particular management action may affect the quality of multiple ecosystem attributes at the same time. The system model has to be initially developed, and should account for all aspects defining the UWS, including engineering, ecological and social aspects in order to properly simulate the impacts of the

Fig. 2. Framework for the integration of ecosystem services into UWS management.

Fig. 3. Urban water system illustration; with the most common considered UWS elements, implemented management actions, and affected ecosystem services.
considered management actions and assess the performance using the previously selected socio-environmental metrics. A key issue in the model building is to properly characterize the relationship between changes in the freshwater ecosystems structure and function on one hand, and ecosystem services on the other hand. We can understand how freshwater ecosystems and services are linked by estimating how changes in the structural characteristics of the ecosystems affect certain biophysical indicators, such as mass of waste processed in the case of water purification service or comparative value of real estate nearer to a water body in the case of aesthetic information service (Corominas et al., 2013; Garcia, 2014). These indicators describe how the provision of the ecosystem service has changed (or is expected to), and so the impact on human well-being can be worked out.

The model must also include the social aspects needed for the valuation of the ecosystem services. This is in fact the final step in the simulation of ecosystem services, and requires the usage of valuation metrics. These allow us to convert changes in the provision of an ecosystem service, measured in biophysical units, into monetary units. Unfortunately, not all the valuation metrics perform equally well for the different ecosystem services (Farber et al., 2006), and there is a lack of standardization in how they are valued (Boithias et al., 2016; Polasky et al., 2015). However, there has been some research on the relationship between ecosystem services and the most appropriate valuation metric (de Groot et al., 2002; Pascual et al., 2010). Although it is generally desirable, the monetary valuation step is not always necessary if the decision is not based on economic outcomes, or there is no need to communicate to the involved stakeholders the outcomes of the management action in monetary terms. Many alternative approaches instead measure effectiveness and “worth” of a service by using biophysical indicators, such as nitrate or phosphorous reduction (Gren, 1995), or social preference (Schach, 2008). Nonetheless, considerations that affect the political or institutional feasibility of the management actions may be difficult to incorporate into computational models. Again, the engagement of stakeholders at this stage is needed to ensure that only relevant options are evaluated.

3.4. Application of the decision-support tool

Using the results of the socio-environmental modeling, the last step implies the application of the decision-support tool, which transforms the modeling results into information that decision makers can easily understand. In those cases when all ecosystem services are expressed in monetary units, CBA or FA are desired. In those other cases when not all services are expressed in monetary units, CEA or the MCA are the most appropriate decision-support tool. As a matter of example, using CBA, demonstrated that a wastewater reuse plan involving urban, agricultural and environmental uses was beneficial if ecosystem services were valued and included in the assessment (20-years NPV of €40,001) (Verlicchi et al., 2012). CEA method including ecosystem services was applied to assess the most cost-effective of various management alternatives to mitigate Cryptosporidium risk, selecting a combination of a spatially targeted 25% restriction in water course access of nondairy cattle and upgrading treatment (Bryan and Kundulu, 2009). FA was applied to assess the economic impact of a water diversion project, demonstrating that, if ecosystem services trade-offs were considered, the project was not affordable (total direct cost and opportunity cost of 262.70 and 256.33 $10^3 Chinese Yuan in 47-years period) (Dong et al., 2011). Finally, the usage of MCA allowed the evaluation of a set of urban floodplain restoration plans considering impact on various ecosystem services as management criteria, and finding as the most optimal management options to increase the hydraulic connectivity in the river (Sanon et al., 2012). Other studies do not use any decision support tool but then quantify the benefits using the estimates of the marginal values associated with management actions specific to each case study (Bateman et al., 2006; Garcia, 2014; Gibbs and Halstead, 2002).

After the implementation of the decision-support tool, and if the user doesn't feel that the goal of the decision making process has been completely achieved, the process can be repeated in a feedback loop to refine some steps of the framework (Fig. 2).

4. Conclusion

We believe that implementing the proposed framework would lead to the following advantages and disadvantages:

✓ Environmental.
   - Advantages: compliance with current legislation; ecosystem and biodiversity conservation while water demands are satisfied; and higher resilience to cope with climate change.
   - Disadvantages: risk of debasing ecosystem services (Gómez-Baggethun and Ruiz-Perez, 2011) by reducing them to a commodity.

✓ Economic.
   - Advantages: efficient use of water resources; provision of a myriad of valuable ecosystem services; revaluing and funding effluent clean up; and payment for ecosystem services schemes.
   - Disadvantages: ecosystem services assessment is expensive.

✓ Social.
   - Advantages: justification of the decision; more participative and equitable decisions; explanation of planning; and opportunity for development of interdisciplinary science.
   - Disadvantages: risk of trivializing the ecosystem services concept.

Despite the clear advantages, implementing our proposed framework is currently constrained by the existing policy framework. A true integration of the different parts of the UWS, as well as other related elements, may only be possible if policies regarding the different elements were themselves also integrated (Everard, 2014). This would mean that integrating these narrowly-framed water management policies, which are currently only associated with a unique water element, would result in the effective and integrated governance of the whole UWS (Pahl-Wostl, 2015).

The management framework that we propose would enable the integrated planning of the UWS to cope more effectively with future predicated social challenges and uncertainties, such as climate change, water scarcity or loss of biodiversity (Poff et al., 2015). In addition, this interdisciplinary form of UWS management, when married with increased technical and financial resources, may help to free up comprehensive management actions, and make the system better and more resilient. Our framework will foster cooperation across sectors and disciplines, which in turn should reduce the cost of assessing ecosystem services. Certainly, the proposed integrated policy framework would require all of us to work towards more participatory decision-making, where the involvement of the ecosystem services stakeholders takes place from the very beginning of the process.

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