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REVIEW

A review of riverine ecosystem service quantification: Research gaps and recommendations

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Abstract

1. Increasing demand for benefits provided by riverine ecosystems threatens their sustainable provision. The ecosystem service concept is a promising avenue to inform riverine ecosystem management, but several challenges have prevented the application of this concept.
2. We quantitatively assess the field of riverine ecosystem services' progress in meeting these challenges. We highlight conceptual and methodological gaps, which have impeded integration of the ecosystem service concept into management.
3. Across 89 relevant studies, 33 unique riverine ecosystem services were evaluated, for a total of 404 ecosystem service quantifications. Studies quantified between 1 and 23 ecosystem services, although the majority (55%) evaluated three or less. Among studies that quantified more than one service, 58% assessed interactions between services. Most studies (71%) did not include stakeholders in their quantification protocols, and 34% developed future scenarios of ecosystem service provision. Almost half (45%) conducted monetary valuation, using 16 methods. Only 9% did not quantify or discuss uncertainties associated with service quantification. The indicators and methods used to quantify the same type of ecosystem service varied. Only 3% of services used indicators of capacity, flow and demand in concert.
4. Our results suggest indicators, data sources and methods for quantifying riverine ecosystem services should be more clearly defined and accurately represent the service they intend to quantify. Furthermore, more assessments of multiple services across diverse spatial extents and of riverine service interactions are needed, with better inclusion of stakeholders. Addressing these challenges will help riverine ecosystem service science inform river management.
5. *Synthesis and applications*. The ecosystem service concept has great potential to inform riverine ecosystem management and decision-making processes. However, this review of riverine ecosystem service quantification uncovers several remaining research gaps, impeding effective use of this tool to manage riverine ecosystems. We highlight these gaps and point to studies showcasing methods that can be used to address them.

KEYWORDS
aquatic, ecosystem management, ecosystem service, human impact, land use, research challenges, river, river management, riverine, sustainability

1 | INTRODUCTION

Riverine ecosystems around the world are home to a rich array of biodiversity (Dudgeon et al., 2006) and play an important role in supporting peoples' livelihoods and traditions by providing them with numerous benefits (FAO, 2015; Postel & Carpenter, 1997), including the provision of food, water and areas for recreation. The diverse benefits that people obtain from ecosystems are known as ecosystem services (Millennium Ecosystem Assessment, 2005a). As demand for riverine ecosystem services continues to increase, their sustainable provision may be jeopardized (Millennium Ecosystem Assessment, 2005b). Indeed, research shows that riverine ecosystems are both disproportionately important for livelihoods and disproportionately threatened (Tockner, Ward, Edwards, & Kollmann, 2002; Vörösmarty et al., 2010). The concept of ecosystem services provides a holistic and adaptable means to evaluate the diverse ways ecosystems contribute to human well-being, making it a promising avenue towards informed riverine management (Schindler et al., 2014; Schröter et al., 2017).

To effectively inform land management and decision making, ecosystem service research must address several challenges (McDonough, Hutchinson, Moore, & Hutchinson, 2017). These include the following: (1) Reducing bias in the types of ecosystem services evaluated, and instead identifying the full range of available and desired ecosystem services on a particular landscape (Chan et al., 2012); (2) Developing scientifically defensible, policy relevant and widely accepted ecosystem service quantification methods (Heink, Hauck, Jax, & Sukopp, 2016; Polasky, Tallis, & Reyers, 2015); (3) Understanding and quantifying interactions among ecosystem services to improve management's ability to account for impacts on multiple services (Bennett, Peterson, & Gordon, 2009); (4) Understanding the diverse spatial and temporal scales at which ecosystem services are provided to reduce the unintended consequences of managing services at mismatched scales (Rodríguez et al., 2006); (5) Including local and relevant stakeholders and community members in ecosystem service research to help identify relevant services and choose appropriate targets and goals of management (Seppelt, Dormann, Eppink, Lautenbach, & Schmidt, 2011). Addressing these challenges is fundamental to the equitable and sustainable management of services.

We review publications quantifying riverine ecosystem services and compile information on the global distribution of these studies, the types and quantities of ecosystem services they evaluate, and the methods used to quantify these ecosystem services. We ask five main questions related to the ecosystem service research challenges outlined above: (1) Which ecosystem services are being quantified in riverine habitats? (2) What are the methods being used to quantify these? (3) How many ecosystem services are studies quantifying, and are studies assessing interactions—that is, trade-offs and synergies—between services? (4) At which spatial extent are riverine ecosystem services being quantified? and (5) Are local and relevant stakeholders being included in quantification protocols? Building on our findings, we highlight research gaps observed across the field and provide recommendations for future riverine ecosystem service research, while pointing to methods to help address these.

2 | DEFINING RIVERINE ECOSYSTEM SERVICES AND KEY TERMINOLOGY

We define riverine ecosystem services as those provided by rivers and the broader landscapes that are hydrologically connected to rivers (associated watershed) (Thorp, Thoms, & Delong, 2006). This definition for riverine ecosystem services incorporates both services that are provided directly within rivers, such as the production of hydroelectricity, as well as services that are not strictly provided *within* rivers, but related to them, such as flood mitigation, irrigation of agricultural fields, and recreational activities such as hiking or camping alongside rivers.

Numerous ecosystem service typologies exist. The Millennium Ecosystem Assessment (MA, 2005a) is one of the most predominantly used typologies, which divides ecosystem services into four categories: cultural ecosystem services (nonmaterial benefits such as recreational activities including swimming or canoeing, the aesthetic beauty of rivers, or their spiritual significance among many communities); provisioning ecosystem services (products obtained from ecosystems, including the supply of freshwater for drinking, and fish); regulating ecosystem services (the benefits obtained from the regulation of ecosystem processes, such as erosion prevention or water purification); and supporting ecosystem services (processes that are necessary for the production of other ecosystem services, such as nutrient cycling and habitat provision; Millennium Ecosystem Assessment, 2005a). Since the MA's publication, numerous researchers have advocated that supporting services be re-classified as ecological processes rather than as services themselves (Carpenter et al., 2009; Hein, Koppen, DeGroot, & Van Ierland, 2006). This discussion contributed to the emergence of another predominant framework, which categorizes ecosystem services into intermediate services, such as water purification, which are important to producing final services, such as the supply of clean water, which result in benefits, such as the enjoyment of drinking clean water (Fisher, Turner, & Morling, 2009). This distinction of the overlap between intermediate services and benefits helps avoid problems related to economic double-counting—the erroneous practice of counting the monetary value of services more than once (Fu et al., 2011). Related, many different aspects of a service can also be measured, including capacity—"an ecosystem's potential to deliver services based on biophysical and social properties and functions," flow—"the actual production or use of the service," and demand—"the amount of a service required or desired by society" (Villamagna, Angermeier, & Bennett, 2013). Each of these aspects reflects a different way of approaching ecosystem service quantification and provides unique information about the supply of, and demand for, services; their comparison can inform us about the sustainability of ecosystem service provision (Wei et al., 2017).

The wide variety of typologies and definitions used to describe ecosystem services reflects the flexibility of the ecosystem services concept to answer diverse questions in varied contexts. While any one typology is unlikely to be suited to all types of studies (Fisher et al., 2009), ecosystem service science is generally improved by providing clear definitions and explanations of typologies (Heink et al., 2016). In this study, we use definitions and categories from the MA to classify the riverine ecosystem services that we identify.

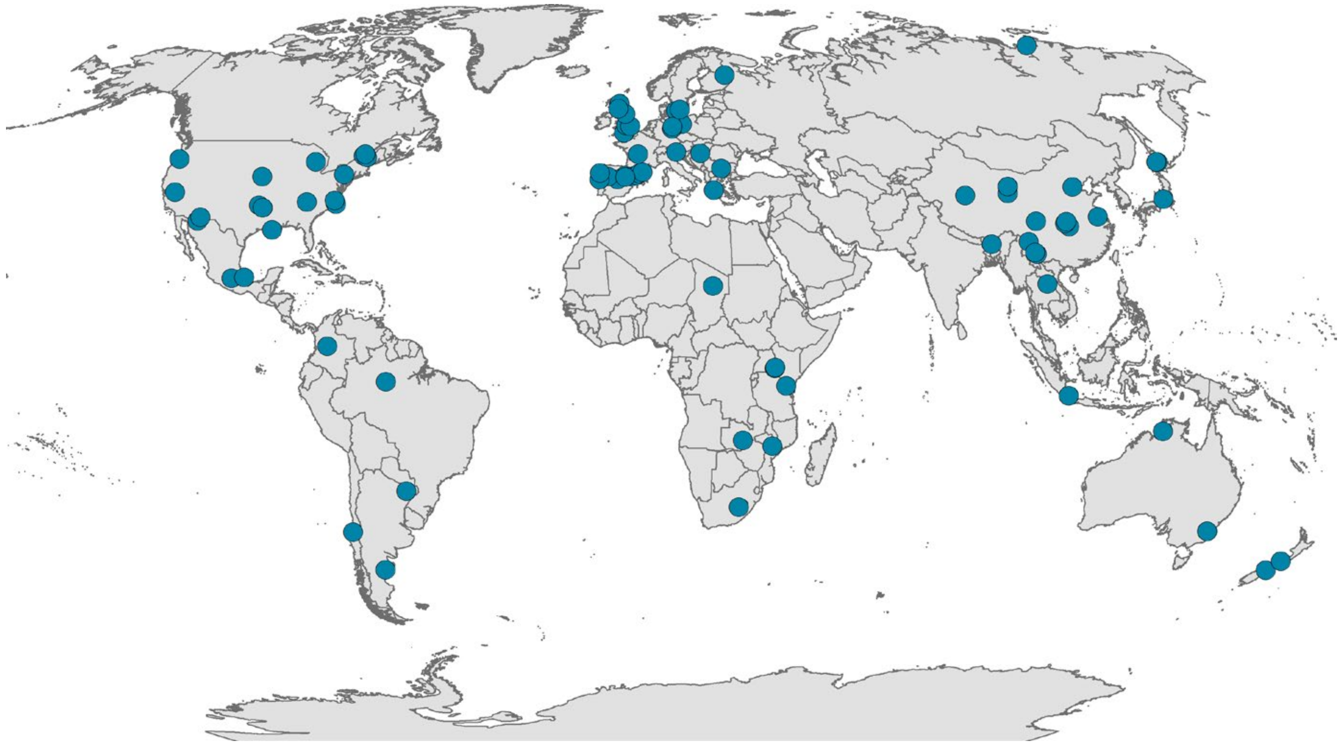

FIGURE 1 Global distribution of riverine ecosystem service studies. Each circle represents the location of a study. A complete list of studies and their exact locations is found in the Supporting Information (Table S1.1 in Appendix S1) [Colour figure can be viewed at wileyonlinelibrary.com]

3 | MATERIALS AND METHODS

3.1 | Data collection and analysis

We identified publications quantifying riverine ecosystem services available via ISI Web of Science and published prior to April 2016 using the search terms: "ecosystem service*" AND "river*." We screened the 1,375 resulting publications and retained English-language publications that self-identified as having quantified one or more ecosystem service in a riverine habitat. Studies that quantified benefits (e.g. water quality, flood regulation) but that did not explicitly self-identify as having quantified an "ecosystem service" were not included as we were interested in the body of literature that actively deems themselves as ecosystem service research. No conference proceedings or book chapters were retained, nor were studies evaluating ecosystem services in estuaries or deltas, as the focus was on peer-reviewed studies measuring ecosystem services provided by freshwater rivers and the adjacent landscapes.

From the screened studies, we identified 89 relevant publications (Figure 1; and see full list of compiled studies in Table S1.1 in Appendix S1). From each study, we compiled quantitative data on the location of the study, the types and numbers of ecosystem services evaluated, and the methods used to quantify services. A detailed description of the data that was collected on ecosystem service quantification and information about how it was collected is listed in the Supporting Information (Appendix S2). Patterns across riverine ecosystem service studies and quantification methods were evaluated using the R core packages (R Core Team, 2016), dplyr (Wickham & Francois, 2016), and visualized using QGIS (Quantum GIS Development Team, 2017) and ggplot2 (Wickham, 2009).

4 | RESULTS

We found that riverine ecosystem service research was concentrated in Europe, China and the United States (Figure 1). Studies evaluated anywhere from 1 to 23 ecosystem services, with the majority (55%) evaluating three or fewer. Of the studies that assessed more than one ecosystem service, 58% qualitatively or quantitatively assessed interactions between a pair or more of services. Still, overall, less than half (45%) of the compiled studies evaluated interactions between ecosystem services (Figure 2).

Across the 89 studies compiled, we identified 33 unique ecosystem services, and a total of 404 ecosystem service quantifications (Figure 3). The five most frequently quantified ecosystem services were recreation and tourism, water supply, water quality, habitat provision, and erosion prevention. Overall, provisioning and regulating services were quantified most often, while cultural and supporting ecosystem services were less frequently measured (respectively, 37%, 33%, 24%, and 6%). We found that ecosystem services from all possible combinations of these four categories were evaluated together in individual studies (Figure 4). Studies that evaluated combinations of ecosystem services that included cultural services (39%) were

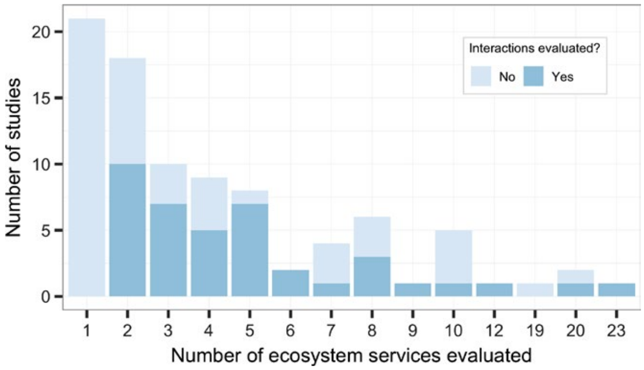

FIGURE 2 Number of ecosystem services quantified in studies conducted in riverine ecosystems, and studies that evaluated interactions between two or more services. Interactions were evaluated descriptively or statistically, and overall, 45% of studies looked at interactions. Looking only at studies that assessed more than one service (68 out of 89 studies), 58% assessed interactions [Colour figure can be viewed at wileyonlinelibrary.com]

underrepresented relative to those that included provisioning (71%) or regulating services (74%).

There was substantial variability among the indicators used to quantify the same ecosystem service types from one study to the next (Figure 5). For example, water quality was quantified 29 times using 25 different indicators, and recreation/tourism was quantified 47 times using 41 different indicators. The majority (64%) of ecosystem services were quantified using indicators that represented one or another of the aspects of ecosystem service delivery—either capacity, flow *or* demand. All other ecosystem services (36%) were quantified using a combination of indicators that represented multiple aspects, with 3% of these ecosystem services quantified using indicators representing capacity, flow and demand together (Figure 6). Of the indicators used to quantify the same ecosystem service across studies, we found that several different aspects were quantified for most services, with no apparent trend in which categories of services might be more likely to be quantified using a given aspect (Figure S3.1 in Appendix S3). Among studies that quantified more than one ecosystem service, only 36% evaluated the same aspect(s) of each of these different services.

Five types of data sources and three different groups of technical methods were used to quantify ecosystem services in the studies we assessed (Figure 7). The majority of services were quantified using some form of secondary data (60%), followed by the use of participatory data (32%), remotely sensed secondary data (23%), remotely sensed data (13%) and field data (10%). Multiple data sources were used simultaneously to quantify 32% of ecosystem services (Figure 7a). The most frequently used technical method to quantify ecosystem services was statistical analysis (descriptive or other, also includes the use of monetary valuation), followed by the use of geographic information

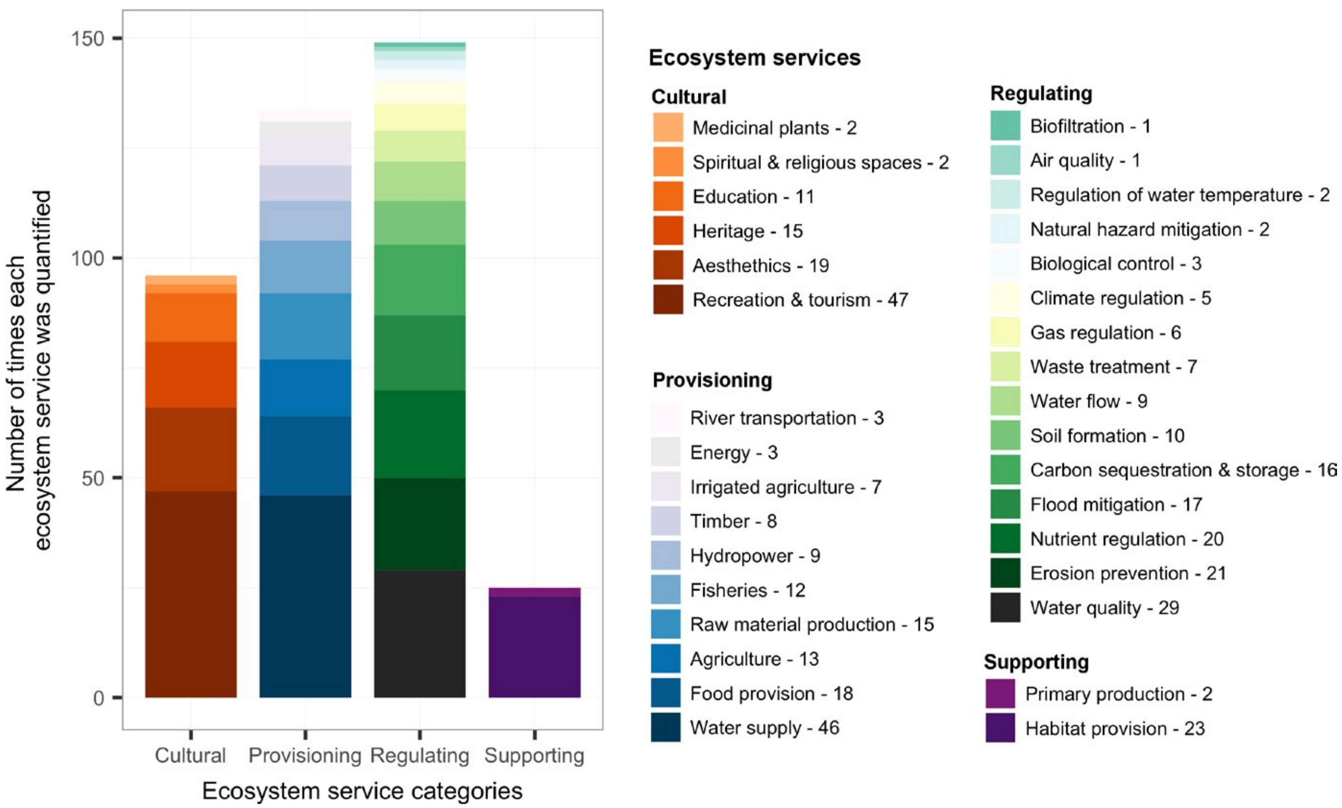

FIGURE 3 Ecosystem services evaluated among the 89 reviewed studies conducted in riverine habitats. The 33 types of ecosystem services quantified are listed in the legend and followed by the number of times each of them was quantified (total of 404 unique ecosystem service quantifications across all studies). Ecosystem services are ordered from most to least frequently assessed from bottom to top and separated by over-arching ecosystem service categories, as defined in the Millennium Ecosystem Assessment. When two ecosystem services occurred the same number of times, they were ordered alphabetically

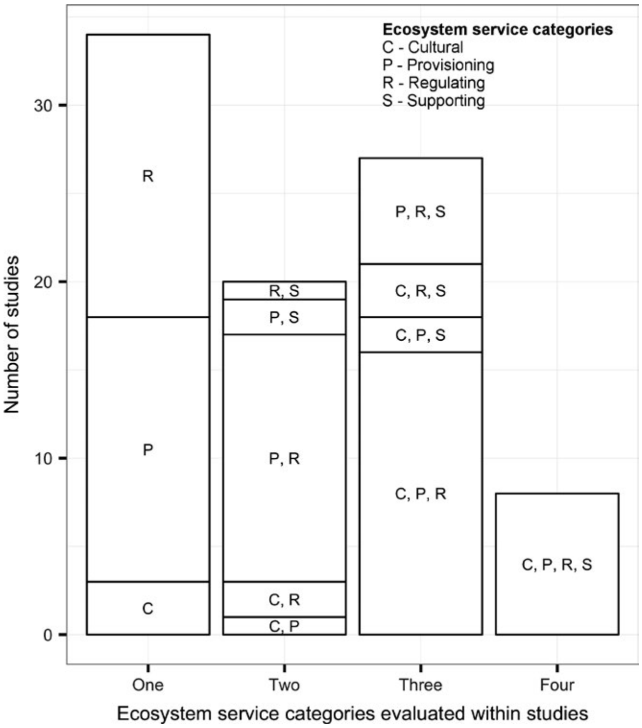

FIGURE 4 Combinations of ecosystem services from over-arching Millennium Ecosystem Assessment categories evaluated within the 89 compiled studies quantifying riverine ecosystem services

systems (GIS), and various modelling tools (Figure 7b). Among the studies that used GIS (n = 33), 42% used hydrographic networks as opposed to land-use data to represent rivers, and 86% utilized data with a 30-m resolution or coarser. Quantitative assessments of uncertainty were conducted in 52% of studies, while 36% qualitatively described uncertainties, and 9% did not mention uncertainty at all. Monetary value was quantified in 45% of the compiled studies, using 16 different methods. Among studies that quantified monetary values, direct price approaches were most frequently used (67% of studies), followed by stated preference (30%) and revealed preference approaches (12%) (Table S4.1 and Figure S4.1 in Appendix S4).

Most studies quantified ecosystem services at the spatial extent of the watershed (Figure 8). Out of the 89 studies assessed, 34% created and evaluated future scenarios of ecosystem service provision. These scenarios were a combination of land use and policy management alternatives (67%) and climate change driven scenarios (33%). Across compiled studies, 70% did not include stakeholder or community engagement. Finally, 20% of studies quantified biodiversity in addition to quantifying ecosystem services.

5 | DISCUSSION

5.1 | Ecosystem services evaluated in the riverine literature

Our results demonstrate the wide variety of ecosystem services provided by riverine habitats and the diverse methods for their quantification in riverine ecosystem service literature. The literature's emphasis on provisioning and regulating ecosystem services mirrors a bias also documented in other reviews for other ecosystems (Martínez-Harms & Balvanera, 2012; Seppelt et al., 2011). This bias is likely widespread because these two categories include ecosystem services that produce, or sustain the production of, material goods, which can increase their perceived importance (Martín-López et al., 2012) and facilitate their quantification and monetary valuation. Erosion prevention was quantified more often in the riverine literature than in general ecosystem service science (Crossman et al., 2013; Egoh et al., 2008). Given the impacts erosion has on other riverine ecosystem services such as the provision of high-quality water, the ecosystem service concept can be a constructive tool to inform decisions geared towards erosion prevention (Frank, Fürst, Witt, Koschke, & Makeschin, 2014).

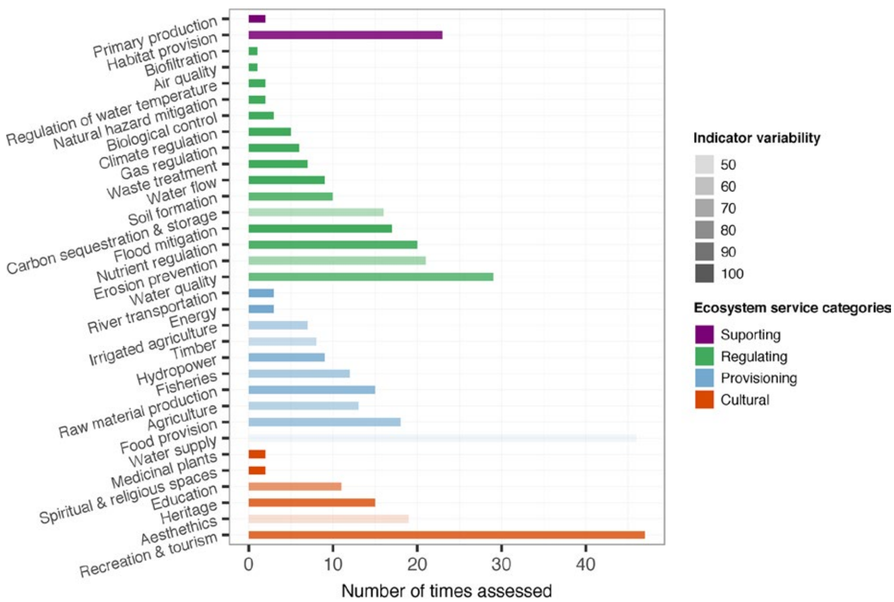

FIGURE 5 The variability among indicators used to quantify each ecosystem service. Indicator variability was calculated as the number of different indicators used to quantify an ecosystem service divided by the total amount of times it was quantified, multiplied times 100. As such, larger numbers and darker colours represent more variability among the indicators used to quantify a given ecosystem service, lighter colours represent more consistent indicator use. [Colour figure can be viewed at wileyonlinelibrary.com]

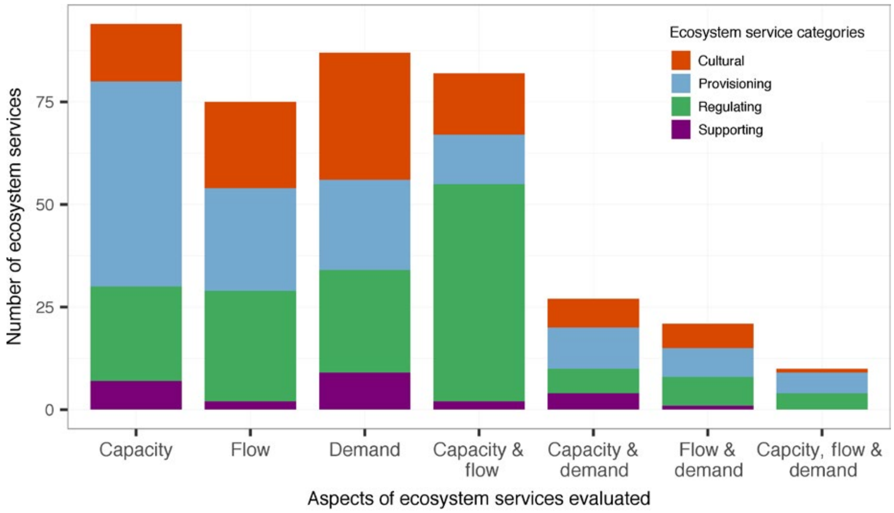

FIGURE 6 Aspects represented by the indicators used to assess ecosystem services. Aspects were determined by reading the description of the indicator used to quantify each ecosystem service and labelling it as representing that services' capacity, flow or demand. Because it was not possible to locate the indicators for eight of the 404 ecosystem services for which information was compiled in this study, this figure only includes data from 396 ecosystem service quantifications [Colour figure can be viewed at wileyonlinelibrary.com]

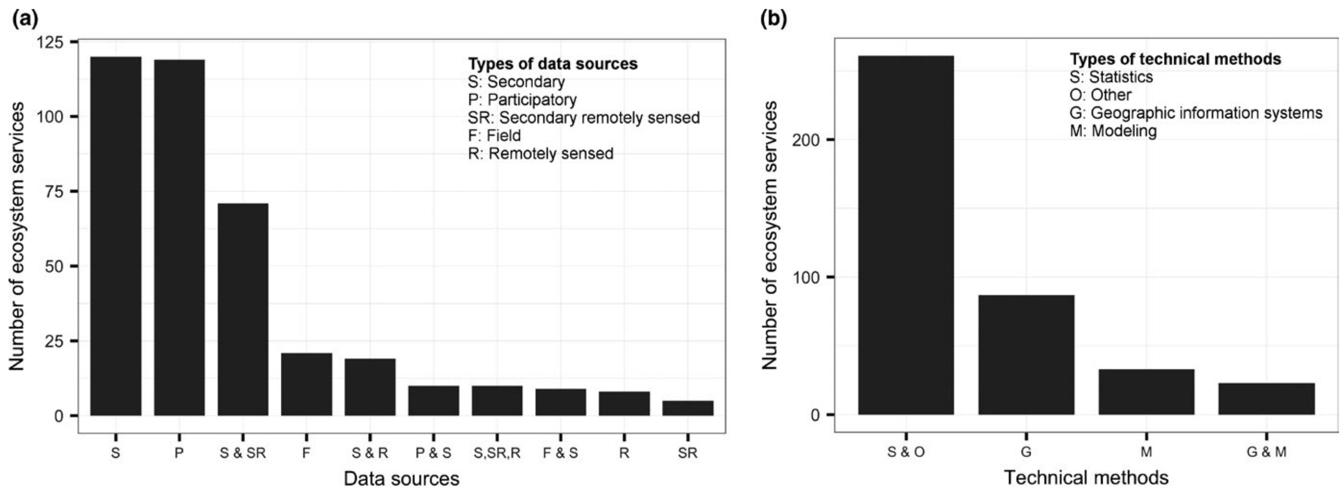

FIGURE 7 Data sources and technical methods used for ecosystem service quantification in riverine habitats. (a) Percentage of ecosystem services quantified using unique combinations of data sources. Combinations of data sources that were used less than 1% of the time are not shown here. (b) Technical data analysis methods for ecosystem service quantification. Numbers indicate what percentage of ecosystem services were quantified using these technical methods. The category "Statistics or other" includes the use of raw data, monetary valuation and other statistical analyses to compute ecosystem service values

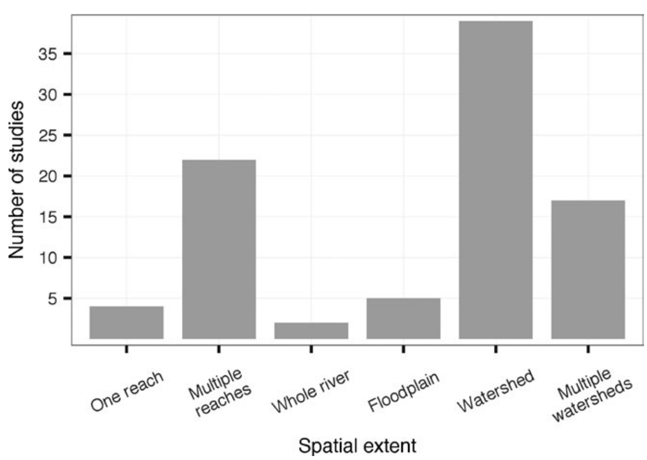

FIGURE 8 Spatial extent at which ecosystem services were quantified across the 89 compiled studies

Within cultural ecosystem services, we observed a bias towards the evaluation of services with clear material value: recreation and tourism were assessed more often than cultural spaces. This may be because the "intangible" dimensions of certain types of cultural services make them difficult to quantify (Chan et al., 2012; Milcu, Hanspach, Abson, & Fischer, 2013; Sanna & Eja, 2017). Nevertheless, intangible ecosystem services remain crucial components of socio-ecological systems and failing to include them in studies that will inform decision making and management strategies can have important consequences. For example, hydroelectric projects that only consider river flow regimes and fish populations, while neglecting other important cultural heritage factors such as spiritual sites have, at times, resulted in significant conflict between First Nations, government and developers in Canada (T8FNs Community Assessment Tbam, 2012; Treaty 8 Tribal Association, 2017).

These results suggest that there is a need for increased attention to ensuring that diverse ecosystem services, spanning all categories, are evaluated across riverine ecosystem service research, as well as within individual studies. Simply knowing that the gap exists is a first step, but actually bridging the gap will require drawing on diverse expertise and resources. Building multi-disciplinary teams, referring to existing frameworks for guidance (e.g. Chan et al., 2012; Plieninger, Dijks, Oteros-Rozas, & Bieling, 2013), and including people with diverse experiences, backgrounds, social status and expertise in the quantification process should help diminish biases (Felipe-Lucia et al., 2015; Gould et al., 2014), and facilitate the identification and inclusion of the wider suite of ecosystem services provided by global riverscapes.

5.2 | Methods used to quantify ecosystem services

Our results illustrate that despite calls urging for the streamlining of ecosystem service indicators (e.g. Heink et al., 2016), the field of riverine ecosystem services does not yet have an established standard. Defined sets of indicators for particular ecosystem services can facilitate comparisons across locations. Yet, there are also benefits to using context and question-specific indicators (Costanza, 2008; Fisher et al., 2009). For example, the concentration of phosphorous may be a good indicator of water quality for human consumption in one location but not in another location where waterborne infectious diseases can be present and should, therefore, be monitored.

The aspect of the ecosystem service being assessed (i.e. capacity, flow, demand) should also affect the choice of indicator; a study measuring the capacity of a landscape to provide water quality would not use the same indicator as one that is measuring local demand for this ecosystem service. Further, each aspect provides different information—understanding the capacity of a landscape to provide water quality does not tell a land manager if that capacity is sufficient to meet local demand (Wei et al., 2017). Yet, few of the ecosystem services studies we compiled even acknowledge the multiple aspects of ecosystem services that can be measured, leaving a great deal of ambiguity regarding what aspect of ecosystem services they are intending to quantify, or why. We also found that only 36% ecosystem services were evaluated considering multiple aspects in tandem; without quantifying and comparing, for example, capacity and flow, it is difficult to understand whether riverine services are being used sustainably (Wei et al., 2017).

The use of secondary data to quantify riverine ecosystem services comes with certain limitations. For example, Di Sabatino, Coscieme, Vignini, and Cicolani (2013) showed that using different types of remotely sensed secondary data in a geographic information system changed the estimate of the annual monetary value provided by rivers from 600 million to 7 billion dollars. Because rivers are linear features that are often small or hidden by vegetation, assessments benefit from using data other than coarse resolution satellite imagery and land-use classifications (e.g. Tomscha, Gergel, & Tomlinson, 2017), suggesting the need for more riverine research adopting higher resolution secondary data.

Information about uncertainty is important for understanding how well ecosystem service quantifications perform, and for knowing under which conditions and with what level of certainty quantifications can be used to inform decision making (e.g. Stürck, Poortinga, & Verburg, 2014). This makes results from the 9% of studies that did not measure or mention uncertainties difficult to use in management. Hamel and Bryant's (2017) publication offers constructive guidance on quantifying uncertainties by discussing the different types of uncertainties associated to ecosystem service assessments and offering practical solutions to quantify these, such as providing ranges of a service value, using sensitivity analyses, establishing common language to discuss uncertainty levels among the actors involved, and enabling conditions for effective knowledge brokerage.

Monetary valuation can help compare ecosystem services to other types of assets and promote the consideration of services that are not accounted for in current global trade markets in management decisions (TEEB, 2010). Yet, monetary valuation techniques can yield inaccurate findings if, for example, markets are distorted, erroneous assumptions are made while determining values, or the biases people tend to have when estimating the financial value of services are not accounted for (TEEB, 2010). Furthermore, certain ecosystem services are extremely difficult to value monetarily, as stakeholders would never consent to trading them (Kenter, Hyde, Christie, & Fazey, 2011). Combining multiple types of valuation can help the constructive use of monetary valuation to inform decision making (e.g. Vollmer, Prescott, Padawangi, Girot, & Grêt-Regamey, 2015).

Only 34% of studies included possible future scenarios. Scenarios are used to develop insights on the potential outcomes of different policies or circumstances (Carpenter, Bennett, & Peterson, 2006). They can also stimulate social learning and facilitate more collaborative decision making (Johnson et al., 2012). In fact, a recent survey of decision makers from across sub-Saharan Africa showed unanimity concerning the utility of scenarios for decision making (Willcock et al., 2016). Thus, to strengthen the utility of riverine ecosystem service research for managers, more research should incorporate scenarios.

Our results illustrate the variability in indicators, data sources and methods used to quantify ecosystem services in riverine habitats. The wide variation in methods reflects the flexible nature of the concept of ecosystem services, which is one of its strengths. Still, for the field to yield useful results in terms of riverine ecosystem management, it is important that valid methods be used to quantify ecosystem services. We suggest that the most critical features of an ecosystem service indicator are that it be clearly and explicitly defined and that it accurately represents the service and aspect it intends to quantify. Although these may seem like evident recommendations that other ecosystem service researchers have already discussed (e.g. Boerema, Rebelo, Bodi, Esler, & Meire, 2016; Heink et al., 2016; Schultz, Johnston, Segerson, & Besedin, 2012), we found that it was not always simple, or even possible, to identify exactly which indicators, data sources and methods were used to quantify which service, and that some of the indicators that were used, such as land use, are known to poorly represent the service studies intended to quantify (Eigenbrod et al., 2010). Using a table to summarize all this information may be a useful way to present which ecosystem services are quantified and how they are quantified (e.g. Table 1).

TABLE 1 Example list of quantified ecosystem services on a fictive river in the province of Quebec, Canada, which demonstrates ecosystem service aspect, indicators, data sources and quantification methods

Ecosystem services quantified	Ecosystem service aspect represented by the indicator (capacity, flow, demand or other)	Description of the indicator used	Data sources (secondary, participatory, remotely sensed, field collected or other)	Methods used to quantify services (use of raw data, statistics, monetary valuation, modelling, GIS or other)
1-Water quality	Capacity to provide water quality	Composite index of bacterial and physico-chemical conditions of water (IQBP)	Secondary data derived from Quebec government "IQBP" database[a]	Use of raw data derived from existing dataset
2-Agricultural irrigation	Capacity for agricultural irrigation given current land use	Amount of water that could be extracted from the river (measured in litres) while respecting environmental flow requirements[b]	Field collected and secondary regional gauge data on flow. Data obtained for the targeted site and comparable rivers with different levels of flow alteration[c] and ecological statuses[d]	Use of raw data, geographic information systems and modelling included in the assessment of Environmental Flow Requirements based on the ELOHA framework
	Flow of agricultural irrigation	Amount of water extracted annually from the river for irrigation of agricultural crops	Government collected data on annual water extraction for agricultural crops, measured in litres[e]	Use of raw data, geographic information systems and descriptive statistics to calculate local annual water use
	Demand for water for agricultural irrigation	Satisfaction level of locals in terms of access to water for agricultural irrigation, rated as high, medium, low or inapplicable	Participatory data derived from interviews with inhabitants of the watershed asking how satisfied they are with the amount of water they have access to annually for the irrigation of agricultural crops	Use of raw data derived from interviews and statistics to calculate watershed average satisfaction level with regard to water access

[a]Data available via www.mddelcc.gouv.qc.ca/eau/Atlas_interactif/donnees_recentes/donnees_iqbp.asp.
[b]Estimation of environmental flow requirement based on the ELOHA framework (Poff et al., 2009. *Freshwater Biology*, 55, 147-170), with the goal of maintaining the rivers current ecological conditions.
[c]Here, we define "flow alteration" as the amount of water extracted annually in litres. Government data[d] on local water extraction would be used to select rivers along a gradient of flow alterations.
[d]Ecological status is estimated with the IQH (Habitat Quality Index-for aquatic habitats), using government established field protocols available online: http://www.mddelcc.gouv.qc.ca/eau/eco_aqua/macroinvertebre/benthos/surveillance.htm.
[e]Data obtained by "information access" request to the provincial government. See the following document for specifications of how measurements are made: http://www.mddelcc.gouv.qc.ca/eau/prelevements/guide-applicationRDPE-entreprises-agricoles.pdf.

5.3 | Assessment of interactions between ecosystem services

The lack of riverine studies that quantitatively or qualitatively assessed interactions between ecosystem services highlights a critical gap. This is because services are not independent, meaning that we must understand interactions to develop management strategies that do not result in unintended consequences (Bennett et al., 2009). Correlations can be used to quantify interactions. For example, Kozak, Bennett, Hayden-Lesmeister, Fritz, and Nickolotsky (2015) identified river transportation as a provisioning ecosystem service and showed that its amount was positively related to the provision of blue crab landings, but negatively related to crawfish landings in the Atchafalaya river, in Louisiana, USA, demonstrating the impacts management decisions related to transportation quotas could have on these different fisheries. In another study, Felipe-Lucia, Comin, and Bennett (2014) quantified 12 ecosystem services and showed which of these tended to increase or decrease at the same time in different land-use types, demonstrating how regional managers could adjust land-use cover to foster the provision of given sets of services. Other methods such as overlap analyses or ordinations can be used to quantify the diverse types of interactions that occur between ecosystem services (Mouchet et al., 2014). In riverine habitats, interactions resulting from the distinct directionality and unique connectedness of rivers across broad spatial scales (Thorp et al., 2006) must also be considered.

5.4 | Spatial extent of ecosystem service quantification

The directional connectivity of riverine ecosystems makes it difficult to disentangle services provided at smaller spatial extents (e.g. water quality of a river reach, hydropower generated by a river) from phenomena occurring at larger spatial extents, such as the hydrologically connected upstream components of the river network (Linke, Norris, & Pressey, 2008). In fact, using different spatial extents to assess riverine ecosystem services or the factors driving their provision yields different patterns of results (e.g. Felipe-Lucia et al., 2014; Norton, Greene, Scholefield, & Dunbar, 2016; Terrado, Tauler, & Bennett, 2015). Further, in rivers, there may be disconnect between the spatial extent at which ecosystem services are produced and the spatial extent at which they are provided, as when downstream water quality is dependent on upstream phenomena (Brauman, Daily, Duarte, & Mooney, 2007). Given the unique spatial properties of rivers, this field would benefit from increasing attention towards the implications of spatial extent when quantifying services and implementing management decisions (Scholes, Reyers, Biggs, Spierenburg, & Duriappah, 2013).

5.5 | Stakeholder inclusion in ecosystem service quantification

Collaborating with stakeholders to identify and quantify ecosystem services can shed light on how people interact with services and which services are important locally, thus improving project outcomes by preventing unintended consequences. For example, land managers of the Cilliwung river in Jakarta, Indonesia, proposed that the river be channelized to avoid annual flooding. Yet, when Vollmer et al. (2015) conducted household surveys on the ecosystem services provided by the river and its riparian zone, the extensive importance of river access for local well-being became clear. This led researchers to propose an alternative management plan, in which the river was surrounded by a slanted, floodable park, preserving numerous ecosystem services provided by river access. In this case, engaging with local communities provided decision makers with a reason to seek alternative management strategies to optimize the provision of multiple ecosystem services of interest in the local community and avoided creating a situation in which important services can no longer be accessed. In planning methods to engage with stakeholders, ecosystem service practitioners should pay careful attention to the scale at which stakeholders are selected for participation (Hein et al., 2006), their profiles and consequent influence (García-Nieto et al., 2015), as well as the relationships among them (Felipe-Lucia et al., 2014), all factors which can influence the outcome of stakeholder engagement. In rivers, it is particularly important that diverse stakeholders from different locations in the studied watersheds be included, as trade-offs in these habitats can be spatially disjointed.

5.6 | Key recommendations for future riverine ecosystem service quantification

Starting from five challenges outlined in the general ecosystem services literature and building from our findings about what has been done in riverine ecosystem service literature in particular, we highlight five recommendations for the future of riverine ecosystem service quantification:

1. Assess multiple diverse ecosystem services.
2. Use validated and reproducible data, methods and indicators, and clearly communicate sources of data and methods.
3. Evaluate the interactions between the ecosystem services assessed, including those that are spatially distant and result from upstream–downstream connectivity.
4. Select the spatial extent and resolution of ecosystem service quantification based on the question of interest while considering directionality, lateral connectivity, and narrow extent of riverine features. Evaluate the implications of using this extent over others.
5. Engage with local and relevant communities/stakeholders to identify and quantify ecosystem services.

Our goal here is not to suggest that every riverine ecosystem service research paper attempt to meet all these recommendations, but instead to highlight research challenges that require increased attention by the over-arching field, and should be acknowledged when discussing the management implications of riverine ecosystem service studies. For the ecosystem service concept to inform riverine habitat management, it is crucial that limitations of the methods that are used be clearly outlined, that researchers work together to find ways to address them in the long term and make their findings accessible, as well as relevant to managers (Wright, Eppink, & Greenhalgh, 2017). The ecosystem service concept is indeed a promising avenue to inform riverine ecosystem management, but the field is still in its infancy. As such, there is a need for more research focusing on how to best meet the recommendations outlined here and more research that develops robust tools and methods to inform land management.

5.7 | Using ecosystem service quantification to inform riverine management

Quantifying the ecosystem services at play on riverscapes is a key step towards being able to talk about them among different actors, compare management options in a systematic way, and use information about ecosystem services to help make informed decisions. Here, we point towards examples of studies that are found in the database of the 89 riverine papers we compiled, and can provide guidance to managers working in comparable contexts. Working across several watersheds, Felipe-Lucia et al. (2014) and Holland et al. (2011) exemplify the use of varied datasets to quantify multiple ecosystem services and their interactions to determine locally appropriate spatial extents of service management. At smaller spatial extents, useful methods are explored by, among others, Vollmer et al. (2015), who use interviews to identify relevant services and future management preferences, and by Acuña, Díez, Flores, Meleason, and Elosegi (2013), who used a Before–After, Control-Impact design to test the effect restoration on river reach services. Polizzi et al. (2015) used questionnaires and monetary valuation to assess if the long-term benefits of restoration can compensate for the initial costs. Scenarios were used to evaluate the consequences of restoration and rehabilitation (Honey-Rosés et al., 2013; Newton et al., 2012), the development of hydro-damming projects (Fanaian, Graas, Jiang, & van der Zaag, 2015) and changes in land use (Stürck et al., 2014) or climate (Fezzi, Harwood, Lovett, & Bateman, 2015). Those working with communities to quantify services may consider using surveys (Butler, Radford, Riddington, & Laughton, 2009), organizing workshops with local group representatives (Crossman, Connor, Bryan, Summers, & Ginnivan, 2010), or using to participatory mapping (Polizzi et al., 2015). Taking into account the caveats we reveal throughout this manuscript and recommendations we provide, managers can build off the methods showcased in the studies found in our database to develop context-specific strategies to quantify riverine ecosystem services, and use their quantifications to guide management decisions.

6 | CONCLUSIONS

Our study outlines the current state of the riverine ecosystem service literature and identifies research challenges that must be addressed for the concept of ecosystem services to better inform riverine ecosystem management. For individual studies, ensuring that the indicators, data and techniques used quantify ecosystem services are well defined, justifiable, validated and reproducible are excellent starting points to move the field forward. More broadly, there is a need to better understand the diversity of ecosystem service interactions in riverine habitats, to consider the implications of using different hydrological spatial extents to quantify services, and to build multidisciplinary teams working within specific locations. These are difficult challenges, but important to ensure that riverine ecosystem service research lives up to its full potential for improving management and decision making in riverine systems and their watersheds.

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AUTHORS' CONTRIBUTIONS

D.H., S.T., C.O.D. and E.B. conceived the ideas and designed the methodology; D.H. collected the data, with contributions by S.T. and C.O.D.; D.H. analysed the data; D.H. led the writing of the manuscript. All authors contributed critically to the manuscript drafts and gave their final approval for publication.

DATA ACCESSIBILITY

Data available from Dryad Digital Repository https://doi.org/10.5061/dryad.km42m (Hanna, Tomscha, Ouellet Dallaire, & Bennett, 2017a). R code to generate all analyses, figures, and findings presented in the manuscript are archived on Zenodo. https://doi.org/10.5281/zenodo.1013254 (Hanna, Tomscha, Ouellet Dallaire, & Bennett, 2017b).

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SUPPORTING INFORMATION

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