Enhancing bioassessment approaches: development of a river services assessment framework

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Abstract: There has been a trend toward increasing anthropocentrism in definitions of river health through the explicit inclusion of societal valuation of ecosystem services provided by rivers. New frameworks and associated indicators of river health are therefore required to centralize ecosystem services within river assessment and management activities. Here, we adopt an anthropocentric conceptualization of rivers to focus on a river's ability to maintain ecological function and structure that support ecosystem services valued by society. We apply this approach to further existing conceptual models of river assessment by identifying how benthic indicators can be linked to valued ecosystem services in a river services assessment framework. This approach extends bioassessment from a focus on assessing departure from reference condition to also include the evaluation of rivers based on their delivery of ecosystem services. Indicators based on benthic processes and assemblages are widely used in river health assessments; thus, these are reviewed to identify those indicators most closely linked with the provision of river ecosystem services. Finally, we illustrate how our approach can be applied to management through contrasting watershed examples, including a highly modified agricultural region and relatively pristine Arctic watersheds. The proposed approach supports an explicit connection between valued ecosystem services and benthic indicators, providing more targeted assessment results for use in river management decision-making.

Key words: benthic indicators, ecosystem services, river assessment, river health, river management framework

Societies value healthy rivers (UNEP 2012) and invest significant funding to sustain them. In a recent study that explored the costs and benefits of river ecosystem maintenance, Feuillette et al. (2016), quoting Large (2008), noted that to restore 3 waterbodies in Normandy, France, €235 M was invested over 6 years, mostly in terms of recurrent costs. To support ongoing maintenance of river health, monitoring is considered essential and is actively practiced internationally, largely with freshwater benthic macroinvertebrates as the focus of assessment observations (e.g., Buss et al. 2015). A variety of approaches have been developed to evaluate biological monitoring data collected from rivers.

These approaches range from site-level summaries of taxonomic composition, often expressed as ecological indices (e.g., richness, diversity, ecological traits), to more complex modeling methods such as the reference condition approach, which ascertains site health by comparing ecological endpoints at target sites with those observed at appropriate minimally altered sites (Wright et al. 2000, Bailey et al. 2004, Hering et al. 2004, Stoddard et al. 2006). These approaches are strongly rooted within the concept of ecosystem integrity, where healthy river ecosystem sites are deemed to include all expected species and ecological functions (Frey 1977, Karr and Chu 1999). However, it is increasingly recog-

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nized that human values, needs, and institutions should be explicitly incorporated into any definition of health (e.g., Meyer 1997, Pahl-Wostl et al. 2013).

Recently, there has been a trend toward increasing anthropocentrism in definitions of river health through the explicit inclusion of societal valuation of ecosystem services provided by rivers (e.g., Vugteveen et al. 2006). Here, we adopt an anthropocentric conceptualization of rivers to focus on a river's ability to sustain ecological function and structure that support ecosystem services valued by society. This definition is more integrative and adaptable than river health definitions centered only on departure from reference condition or ecological integrity (*sensu* Karr and Chu 1999) and can be integrated into existing designated use frameworks and regulatory standards, such as those applied as part of the US Clean Water Act (CWA; 1972, and as amended, U.S. Code title 33, §§1251–1387). In this way, our definition encourages a fuller exploration of ecological status for all rivers, which, following careful testing and establishment of indicators, will lead to increased valuation of river systems that are inherently intertwined with human activities. Moreover, our conceptualization of river health enables a dynamic approach to defining the value of rivers, which could include ecological integrity, through explicit acknowledgement that values can change across time and space to fit the needs and priorities of stakeholders in any geographical and societal context. Thus, our definition empowers stakeholders to make more informed decisions about using rivers, such that managers can set regulatory standards that ensure all valued services that benefit society are maintained.

Freshwater, and particularly river, ecosystems are recognized as providing key ecosystem services under 4 categories: provisioning (food and water), regulating (flood control and water purification), supporting (nutrient cycling), and cultural (recreation; Covich et al. 2004a, MEA 2005). Delivery of ecosystem services and associated enhancement of human well-being have been conceptually linked with ecosystem functioning, which in turn depends on biodiversity (MEA 2005). Empirical demonstrations of the linkages between ecosystem services, ecosystem function, and biodiversity are rare (Covich et al. 2004a), in large part due to the complexity of the relations and, thus, the extensive quantitative data and analyses required. Nevertheless, there are an increasing number of studies showing at least modest correlations between ecosystem service delivery and biodiversity. For example, a study by Pinto et al. (2014) explicitly linked biodiversity, ecosystem functioning, and ecosystem services in benthic environments of estuarine systems.

Recognition that strong dependencies exist between the delivery of ecosystem services and different attributes of ecological function and structure present an opportunity to improve the capability of environmental monitoring

and assessment to inform management of river health. For example, Reyjol et al. (2014) suggest the incorporation of river ecosystem services into the European Water Framework Directive could provide a common language that could allow all stakeholders to address their needs in river restoration activities. Our purpose is to develop a river services assessment framework that builds upon current, stressor-based river health indicators by relating river ecosystem services to indicators of ecological structure and function. Our approach explicitly connects valued ecosystem services with appropriate indicators, to provide more targeted assessments for use in river management decision-making. Paetzold et al. (2010) proposed a similar approach to assess ecosystem health through analysis of ecosystem service profiles, which they define as “the overlap between societal expectations for, and the sustainable provision of, suites of ecosystem services.” Such analyses provide a means of gauging the current level of service delivery relative to societal expectations. We explore these ideas of river services through the lens of river benthos function and diversity because the benthos is a central ecosystem service provider in rivers.

The benthos possesses numerous structural and functional features that exemplify its central role in providing ecosystem services that underpin river health. The sediment-water interface is a biogeochemical hot spot, playing a disproportionate role in chemical transformations and biological productivity, especially in fast-flowing reaches where water column production and respiration are limited by short water retention times. In shallow, oxygenated waters, much of the total primary production occurs on submerged surfaces (Lamberti and Steinman 1997). In deeper, hypoxic waters, benthic habitats contain large reservoirs of detritus that fuel microbial productivity (Fischer and Pusch 2001) and associated nutrient transformations, including denitrification (Stief 2013). Moreover, benthic secondary production may be substantial (Benke 1998) and provide an energy source for higher trophic levels including fish and other wildlife. In addition, certain invertebrates that achieve large biomasses can modify their environment through processes of filtration and bioturbation (Vaughn and Hakenkamp 2001, Covich et al. 2004b). Benthic indicators of structure (e.g., percent sensitive taxa) and function (e.g., organic matter breakdown) have a history of use in river health assessment (Young and Collier 2009), but these indicators are typically measured without explicit consideration of how they link with ecosystem services.

Our primary aim is to build on existing conceptual models of river health by constructing a river services assessment framework that identifies how benthic indicators of ecological structure and function can be linked with valued ecosystem services. This approach extends bioassessment from the measurement of ecological integrity to include the assessment of the extent to which rivers provide differ-

ent ecosystem services. Bioassessment indicators designed to measure benthic processes and taxonomic assemblages are widely used in river health assessments. We highlight those that offer potential as predictors of river ecosystem services. Finally, by providing contrasting examples of a watershed highly modified by agricultural and relatively pristine Arctic watersheds, we illustrate how our approach has broader application to ecosystem management.

RIVER SERVICES ASSESSMENT FRAMEWORK

Most rivers, especially those flowing through highly developed or urbanized landscapes, support a range of competing and ever-changing societal demands (Arthington et al. 2010). These demands may change rapidly and unpredictably through time. For example, erosion control and flood mitigation may be required seasonally, while the need for nutrient mitigation may increase over time associated with the expansion of urban and rural developments. Similarly, ecosystem service prioritization will vary geographically, with users expecting different services from headwaters and smaller tributaries than they do of larger tributaries and main stems. Therefore, it would be useful to prioritize the different ecosystem services desired from specific rivers

within an adaptive management context that recognizes variable, shifting, and sometimes competing interests.

Our framework guides the evaluation and assessment of rivers by explicitly identifying connections between benthic indicators and river ecosystem services (Fig. 1). The initial step for monitoring and managing river ecosystem services involves identifying those river ecosystem services that stakeholders value and that improve or maintain human well-being (i.e., provisioning, regulating, supporting, or cultural; Hattam et al. 2015). This step parallels existing approaches used in Environmental Impact Assessment (EIA), such that ecosystem service delivery can be linked to valued ecosystem components (VECs) as part of the EIA process (e.g., Sinclair et al. 2017). Furthermore, just as elicitation of expert opinion and extensive public consultation are central to VEC selection, a similar process for selection of valued river ecosystem services can be employed (e.g., Hattam et al. 2015). Following identification of valued river ecosystem services, we propose an integrated, two-step process that links establishment of targeted provision levels with benthic indicator selection (Fig. 1). Specifically, stakeholders and managers would establish target provision levels for each valued service, and river scientists would select benthic indicators that best assess the status of those services.

Figure 1. River services assessment framework illustrating how river ecosystem services could be used to enhance river health assessment. Valued river ecosystem services are identified by stakeholders who interact with managers and researchers to establish targeted provisioning levels. In doing this, potential trade-offs among ecosystem services are identified, informing an adaptive cycle of reviewing and revising target provision levels. Benthic indicators of ecological structure and function are selected and associated indicator benchmarks established based on relationships with targeted levels of service provision. Monitoring and assessment of indicators is then undertaken to determine whether system performance meets desired provision levels. Results of indicator assessments are used to inform a cycle of review and adaptation of river management strategies to achieve ecosystem service targets.

Decisions regarding establishment of target provision levels of ecosystem services will necessarily be driven by shifting, and possibly competing, societal needs and demands (Fig. 1). In fact, the optimization of one service can influence the physical and biological processes that provide and maintain other services (Helfenstein and Kienast 2014). Moreover, trade-offs in ecosystem services (Bennett et al. 2009) that support societal use and maintain ecosystem quality may result in ecosystem disservices, that is, enhancements in one or more ecological services that reduce or impair the capacity of the system to provide other ecosystem services. These trade-offs have the potential to cause an overall net reduction of benefits at an ecosystem scale. For example, bioturbation from native and invasive fish and crayfish (e.g., Asian Carp and red swamp crayfish) can stimulate sediment nutrient release, potentially enhancing ecosystem productivity. However, bioturbation may also release toxic contaminants stored in the sediment and reduce water quality, which can inhibit production of valued aquatic resources (Matsuzaki et al. 2009, Fischer et al. 2013). Similarly, the production of aquatic plants could be used to sequester excess nutrients, but the increased biomass of plants may restrict water and sediment transport and reduce dissolved oxygen concentrations (Caraco and Cole 2002). Thus, identification and evaluation of trade-offs among ecosystem services, and their potential unintended consequences, will be a necessary part of an iterative, ecosystem service-based approach to river monitoring and management (Fig. 1). This process would follow from employment of expert approximation of river ecosystem services values and conditions as described by Helfenstein and Kienast (2014). Importantly, our framework allows for the simultaneous assessment of the status of multiple river ecosystem services. Therefore, in cases where more than one river ecosystem service is valued, the approach permits managers to evaluate the relative and collective benefits produced from management actions that target different ecosystem services. This approach allows for an adaptive management cycle, where measured trade-offs between different ecosystem services inform the iterative review and revision of targeted provisioning levels.

Alterations of ecosystem services and VECs can be very difficult to detect and monitor (Wood et al. 2000). Our approach addresses this challenge by directly linking the indicator with the service of interest (Fig. 1). We propose that benthic ecologists could provide a suite of indicators to assess the status of valued river ecosystems services. Associations between benthic indicators and service provision would then be quantified and used to establish indicator benchmarks that represent targeted provision levels. The selected benthic indicators would be monitored to enable assessment of each indicator against the established indicator benchmark. Assessment results would then inform a cycle of review and adaptation of river management strate-

gies for achievement of ecosystem service targets. This review process could include causal investigations that would determine the stressors responsible for preventing attainment of targeted provision levels.

BENTHIC INDICATORS OF ECOSYSTEM SERVICES

Our river services assessment framework incorporates indicators that directly link with the ecosystem services that society values from a given river system (Table 1). These ecosystem services include commercial, subsistence, and recreational fisheries; water purification; primary production; decomposition; pest/disease control; and erosion control (MEA 2005). The benthos of rivers directly and indirectly support many of these valued ecosystem services by providing a source of food and habitat for other organisms and by contributing to biogeochemical cycling, contaminant removal, disease suppression, and geomorphic stability. Accordingly, many existing measures of benthic function and structure could be useful as indicators of the status of river ecosystem services. For example, benthic organisms enhance and maintain fisheries through their role as food sources (Wallace and Webster 1996). Key properties of the benthic community known to be linked with fishery profitability and sustainability, such as biomass, diversity (taxonomic and trait), and stability (Pinto et al. 2014), could therefore be informative as indicators of probable and realized impacts of past management decisions. Similarly, many benthic organisms, including bivalves and macrophytes, play a role in purifying river water by assimilating nutrients and contaminants. This ecosystem service provides clean water for irrigation, agriculture, and human consumption, while disposing of wastes. Nevertheless, an important limitation to the adoption of our framework for river service assessment is the limited understanding of mechanistic connections among specific ecosystem services, ecological function, and biodiversity.

Our approach of centering river health management on ecosystem services incorporates the flexibility to allow application across a range of stakeholder priorities and rivers of contrasting ecological status. For example, in the Canadian Arctic, climate change and associated environmental effects on largely pristine streams and rivers are a threat to subsistence harvesting of fish and other aquatic wildlife (e.g., waterfowl) by indigenous peoples. In this case, protection of the natural diversity and resilience of these rivers is the primary goal. In contrast, in situations where rivers have a long history of intense human manipulation, the valued ecosystem services may be quite different. For example, in the Red River valley of southern Manitoba, societal development has focused on enhancing water transport and, most recently, water purification as the most valued services of streams and rivers. An advantage of our framework is that, despite the stark contrast in the two examples,

Table 1. Links between river ecosystem services and example benthic indicators of river health for service delivery assessment. The assessment framework process begins at the left and moves to right, with the key river ecosystem services first identified through a broader consultation process.

River ecosystem service	Role of benthic ecology	Ecological function and structure	Indicators of river health	Relationship	Citations
Fisheries and recreation (commercial, recreational and subsistence fishing, hunting, bird watching, dragonflies)	Benthic organisms as food	Biodiversity	Taxonomic diversity	↑ diversity and stability =	Heino et al. 2005
			Trait diversity (e.g., functional feeding groups)	↑ varied, resilient, and profitable fisheries	
			Community Stability		
			Trophic metrics (e.g., Layman metrics)		
			Ash-free dry mass of periphyton	↑ biomass of high-quality food = ↑ biomass of fish and more profitable fisheries	
			Gross Primary Production		
			Algal quality (e.g., N and P, fatty acid content)		
			Net Ecosystem Respiration		
			Invertebrate density		
			Rooted macrophyte and bryophyte biomass	↑ biomass = ↑ habitat complexity	
Water purification	Benthic organisms as habitat	Habitat Complexity	Bivalve biomass	↑ habitat complexity = ↑ diversity and abundance	Downes et al. 2000; Vaughn and Hakenkamp 2001; Taniguchi et al. 2003; Taniguchi and Tokeshi 2004; Dibble and Pelicice 2010; Mykrä et al. 2011
			Filamentous algae biomass		
Water purification	Nutrient cycling and removal from runoff and wastewater	Nutrient uptake and assimilation capacities	Uptake lengths	↓ uptake length = ↑ assimilative capacity	Peterson et al. 2001; Vaughn and Hakenkamp 2001; Marti et al. 2004; Bernot and Dodds 2005; Lottig and Stanley 2007; Cardinale 2011
			Denitrification		
			Algal species diversity	↑ denitrification = ↑ removal rate	
			Macrophyte biomass		

Contaminant removal	Filtering of water, transformation and sequestration of contaminants	Water filtration rate (e.g., bivalves, sponges) Filter feeder biomass Rooted macrophyte biomass	↑ rate of filtration/storage = ↑ removal of contaminants	Herbes and Schwall 1978; Scholz and Xu 2002; Muñoz and Guieysse 2006
Primary production	Fixation of inorganic carbon; production of oxygen	Microbial transformation Gross primary production Algal biomass (chlorophyll a) Plant biomass	↑ primary production = ↑ oxygen and carbon availability for aquatic organisms	Naiman et al. 1987; Broth-ers et al. 2013; Walters et al. 2015
Decomposition/soil formation	Organic matter processing	Net Ecosystem Respiration Microbial biomass and diversity Litter break-down rates	↑ microbial activity = ↑ Organic matter processing	Jackson et al. 1995; Hieber and Gessner 2002; Gulis and Suberkropp 2003; Greenwood et al. 2007
	Mechanical break-up	Shredder/collector biomass and diversity Litter break-down rates	↑ shredder/collector activity = ↑ Organic matter processing	Covich et al. 1999, 2004; Cross et al. 2005
	Bioturbation	Burrower biomass (e.g., crayfish)	↑ burrower activity = ↑ organic matter mobilization	Covich et al. 1999; Vaughn and Hakenkamp 2001; Covich et al. 2004;
Pest/disease control	Suppression of pathogen outbreaks	Taxonomic diversity Trait diversity (e.g., functional feeding groups)	↑ biodiversity = ↑ protection from pathogens	Johnson et al. 2013; Benbow et al. 2014
Erosion control	Habitat stability	Rooted macrophyte and bryophyte biomass Net-spinner biomass	↑ biomass = ↑ substrate stability	Stream Bryophyte Group 1999; Cardinale et al. 2004; Fritz et al. 2004

it can accommodate both scenarios by focusing indicator selection and associated assessment benchmarks on the valued services of the system.

The River Ecosystem Services Framework aligns with criteria put forward in recent calls to apply procedures, such as defining goals depending on context, developed for the medical sciences (e.g., Eloise et al. 2017). In particular, the framework encourages setting standards and applying appropriate indicators that are individualized for river systems based on optimizing desired ecosystem services. Depending on societal and institutional goals, such indicators and standards could be traditional measures of ecological integrity based on biodiversity or ecological function at pristine reference sites. Alternatively, river health objectives may be focused on providing services that do not necessarily require maintenance of pristine reference conditions. Our approach would be especially advantageous for riverine ecosystem management where human uses of rivers are pervasive and reference conditions are absent, which challenges managers to identify appropriate benchmarks (Davies and Jackson 2006; Stoddard et al. 2006). Even where suitable proxies for pristine conditions exist, it is arguable whether river management based on departure from reference conditions is practical in contexts where rivers serve multiple, often conflicting, socioeconomic functions. Indeed, assessments based on absolute or tiered departure from reference conditions (e.g., biological condition gradient (Davies and Jackson 2006), European Water Framework Directive (WFD; 2000/60/EC) have the potential to undervalue existing functions of working rivers (i.e., rivers that are managed to accommodate a broad range of human uses) by highlighting degradation rather than functionality. Moreover, in situations where return to reference conditions may be impractical, managers and regulators may be frustrated by assessments that provide a lengthy list of impairments that cannot be fixed. Our framework emphasizes a river's capability to support valued ecosystem services and thus provides a path forward for more informed management of these anthropogenic river systems.

Implementation of our framework into monitoring, assessment, and management of river health requires research to address existing knowledge gaps regarding the processes and controls through which benthic communities and processes link to ecosystem services. For example, Bernhardt et al. (2018) describe how studies spanning multiple spatiotemporal scales are needed to establish the interactive relationships between nutrient cycling and river metabolism as well as the external controls on that relationship. Establishing empirical links between ecosystem services and both biodiversity and ecosystem functions will be critical for validating the potential use of the many benthic indicators described in our paper. Establishing indicator-service relationships will also be needed to identify indicator benchmarks that reveal whether desired levels of ecosystem ser-

vices have been achieved for individual river systems. As discussed by Feld et al. (2010), benchmarks related to desired service levels are required to enable objective assessment of temporal and spatial trends in those services. Setting river ecosystem services benchmarks is currently hindered by limited understanding of the relationship between benefits to human well-being and service provision. Moreover, there is a need to generate models that can predict how service provision is likely to be affected by future climate and land use changes (Schernewski et al. 2018). Such models would enhance adaptive management by allowing decision makers to set service target levels that align with societal and institutional goals for human well-being.

ILLUSTRATION OF HOW THE FRAMEWORK CAN BE APPLIED

Case study 1: Arctic freshwaters

The biodiversity of Arctic freshwater ecosystems is increasingly threatened by climate change and human development (Heino et al. 2009). Changes in the physical and chemical properties of freshwater systems that will result from modified water temperature, and ice cover regimes, thawing permafrost, and changes to hydrological processes are all expected to directly affect ecosystem structure and function (Culp et al. 2012). Arctic countries through the Circumpolar Biodiversity Monitoring Program (CBMP) have developed monitoring approaches that would measure shifts in freshwater biodiversity. The CBMP defines ecologically pivotal focal ecosystem components for lakes and rivers, such as the benthos, as central parameters for the monitoring approach.

The CBMP monitoring framework for arctic rivers could be enhanced by using our framework (Fig. 1) to assess and maintain river health in the face of a changing climate. In this case, a valued ecosystem service is the provision of sustaining fish biomass for subsistence fisheries. Because of the difficulty in accurately assessing fish populations in a timely manner, indigenous communities could set target provision levels to be assessed with benthic indicators of the amount and type of food available to fish (e.g., invertebrate diversity and abundance; Table 1). A benefit of applying the framework in this case arises from the ability to provide stakeholders with simple indicators that can measure the status and trends of ecosystem components directly related to fisheries. Assessment of these indicators could inform future management decisions to protect traditional fishing grounds and maintain ecological resilience.

Case study 2: Red River Valley

Lake Winnipeg is the 10th largest lake in the world and, like many such ecosystems in close proximity to large human populations, has undergone rapid eutrophication in the

past 2 decades (Schindler et al. 2012). Recent water quality monitoring has identified that the major source of nutrients entering Lake Winnipeg come from tributaries draining the Red River watershed. As a result, there has been strong interest in assessing and managing the conditions of Red River tributaries as both a cause and potential solution to Lake Winnipeg's eutrophication problem. The catchments of Red River tributaries are intensively managed for agricultural production (Yates et al. 2012), and much of the channel network was historically modified to enhance water transport supporting agricultural drainage.

As such, a key valued ecosystem service of these rivers is water transport. However, with growing concern regarding Lake Winnipeg, there is also an interest in managing these streams to enhance water purification services to reduce nutrient losses associated with agricultural runoff to downstream ecosystems. Applying our framework for river health assessment (Fig. 1) to the Red River Valley would entail identifying indicators associated with water purification. As outlined in Table 1, direct measurements of nutrient processing would include denitrification rates and nutrient uptake lengths, whereas indirect measures could include gross primary production and biomass of primary producers. River services related to water transport of floodwaters would not be expected to be enhanced through improved benthic diversity or function. For example, nutrient removal and assimilation might be maximized by 1) slowing water travel times to increase exposure to sediments and 2) maximizing plant growth to retain nutrients. Both of these actions could negatively affect water transport because excess macrophyte biomass can restrict water flow. Managers would thus need to balance the trade-offs between nutrient processing and water transport by applying our proposed framework iteratively through scenario modeling or adaptive management strategies (Fig. 1) to find the balance that most benefits society.

SUMMARY

In this paper we have built on existing definitions and frameworks of river assessment and have explicitly linked ecosystem services with benthic function and structure. By focusing on a river's ability to support valued ecosystem services through the maintenance of ecological function and structure, we were able to construct a novel framework incorporating powerful adaptive management cycles that can be applied for the assessment of river ecosystems. The proposed framework would lead to identifying explicit connections between valued river ecosystem services and benthic indicators, thereby providing more targeted assessment results for use in river management. An important advantage is the capability to simultaneously assess management actions aimed at different and potentially conflicting river uses. Additionally, we have provided a suite of benthic indica-

tors that should undergo future testing to establish the empirical connection between these measures of benthic structure and function and the valued river ecosystem service of interest. Our emphasis on a river's ability to support ecosystem services valued by society is unashamedly anthropocentric, and indeed it was our explicit purpose to recognize that all rivers, from free-flowing wild rivers to canalized waterways, are managed for human uses. This strong connection between societal requirements and river ecosystem management leads us to believe that our framework can support explicit recognition of the benefits society receives from river ecosystem services and can encourage more systematic management of river futures.

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