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Integrating the social, hydrological and ecological dimensions of freshwater health: The Freshwater Health Index

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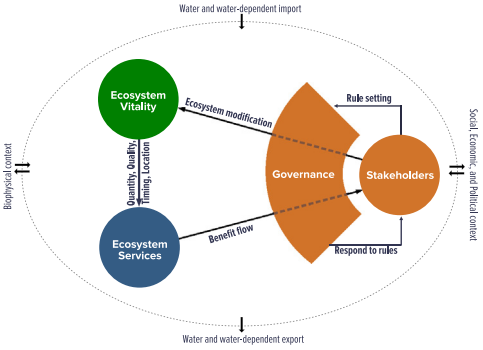
HIGHLIGHTS

- A social-ecological framework is developed to assess freshwater health.
- The framework links ecological, hydrological, and social parameters.
- A set of indicators, the Freshwater Health Index, guides quantitative assessments.
- The Index can be used to monitor changes or compare modeled scenarios to a baseline.

GRAPHICAL ABSTRACT



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ABSTRACT

Degradation of freshwater ecosystems and the services they provide is a primary cause of increasing water insecurity, raising the need for integrated solutions to freshwater management. While methods for characterizing the multi-faceted challenges of managing freshwater ecosystems abound, they tend to emphasize either social or ecological dimensions and fall short of being truly integrative. This paper suggests that management for sustainability of freshwater systems needs to consider the linkages between human water uses, freshwater ecosystems and governance. We present a conceptualization of freshwater resources as part of an integrated social-ecological system and propose a set of corresponding indicators to monitor freshwater ecosystem health and to highlight priorities for management. We demonstrate an application of this new framework —the Freshwater Health Index (FHI) — in the Dongjiang River Basin in southern China, where stakeholders are addressing multiple and conflicting freshwater demands. By combining empirical and modeled datasets with surveys to gauge stakeholders' preferences and elicit expert information about governance mechanisms, the FHI helps stakeholders understand the status of freshwater ecosystems in their basin, how ecosystems are being manipulated to enhance or decrease water-related services, and how well the existing water resource management regime is equipped to govern these dynamics over time. This framework helps to operationalize a truly integrated approach to water resource management by recognizing the interplay between governance, stakeholders, freshwater ecosystems and the services they provide.

1. Introduction

Ensuring freshwater security is one of humanity's greatest natural resource challenges, with 4 billion people experiencing water scarcity in at least one month of each year (Mekonnen and Hoekstra, 2016). Burgeoning human populations will increase demand for this finite resource, while pollution of rivers, lakes and catchments (Malaj et al., 2014), groundwater depletion (Famiglietti, 2014), climate change-induced intensification of droughts (Dai, 2013) and floods (Hirabayashi et al., 2013) will impose ever greater pressure on freshwater resources, threatening biodiversity, food security, economic growth and human well-being. Degradation of freshwater ecosystems and the services they provide is a primary cause of increasing water insecurity and threats to biodiversity (Dudgeon et al., 2006), raising the need for integrated solutions to freshwater management (Vörösmarty et al., 2010; MEA, 2005). Integrated approaches to freshwater sustainability require a coherent framework that integrates the multiple, sometimes conflicting, dimensions of freshwater security to guide the evaluation of the various freshwater ecosystem services, the trade-offs between them, and how they can be sustainably managed.

There are a variety of existing methods and indicators for characterizing these multi-faceted challenges, though they are typically biased toward a disciplinary (e.g., hydrology, ecology, or economics) framing of the problem (Vogel et al., 2015). Pires et al. (2017) evaluated water-related indicators against social, economic, environmental and institutional criteria and find that integrative, multi-metric indices are best-suited to measuring the complexity of water resource sustainability. Vollmer et al. (2016) reviewed 95 distinct indices (and indicator frameworks) and found that although a subset of these multi-metric indices included biological, physical, and social indicators, they typically did not consider interactions among these dimensions, such as the link between ecological function and ecosystem services. For example, the role that freshwater ecosystems play in providing and regulating water storage and flows for human use is frequently overlooked in water resource management (Baron et al., 2002; Green et al., 2015).

Such issues are at the heart of research on social-ecological systems (SES), which attempts to couple social and natural systems (Berkes et al., 2002). Integrated water resource management (IWRM) does incorporate social and ecological dimensions, and it is increasingly reflected in national legal and policy frameworks. However, it has long experienced an implementation gap attributed, in part, to difficulties in measuring its impacts and an inability to apply prescriptive ideals (e.g., holistic management, robust participation) to the practical challenges of decision-making (Giordano and Shah, 2014). Hence, new approaches, analytical tools and agreed-upon benchmarks to assess progress are needed that can bridge science, policy and practice in IWRM (Martínez-Santos et al., 2014). And as Sullivan and Meigh (2007) note, quantitative indices provide an imperfect but useful tool to incorporate scientific knowledge alongside traditional knowledge and cultural values in IWRM.

To meet the challenges of ensuring freshwater security, a conceptualization of freshwater resources as social-ecological systems is required, along with a set of indicators to measure freshwater health and highlight areas for management. “Freshwater health” is defined here as the ability of freshwater ecosystems to deliver ecosystem services and benefits, sustainably and equitably, through effective management and governance. This definition of health is a departure from existing comparable terms such as “river health” (e.g., Boulton, 1999; Karr, 1999; Dos Santos et al., 2011) or “ecosystem health” (e.g., Xu et al., 1999; O'Brien et al., 2016), which use ecological endpoints as proxies for an ability to meet human demands. By defining health as an ability to actually deliver services, and recognizing the role of governance in this, we adhere closer to definitions presented by Meyer (1997) for “stream health” and Vugteveen et al.'s (2006) definition of “river system health”, both of which propose including information on human attitudes and social institutions. We thus define sustainable water use as the long-term use of water in sufficient quantity and with acceptable quality to support human well-being and socio-economic development, to ensure protection from water-associated disasters, pollution and disease, and to preserve ecosystems.

In this paper, we describe development of a framework and accompanying tool, the Freshwater Health Index, that draws attention to the relationships between healthy freshwater ecosystems, the ways in which they are governed by stakeholders and the benefits they provide, using an array of indicators that can be applied to a wide range of decision contexts at the scale of drainage basins. We begin by presenting a conceptual framework, which characterizes the social-ecological nature of freshwater health and guides the selection of indicators. Next, we define the indicators and propose suitable metrics. We then illustrate the utility of the FHI by applying it in a real-world context: the Dongjiang (East River) basin in China. We conclude by discussing the promise and limitations of such an approach and offer recommendations on applications in other basins and contexts.

2. Conceptualizing freshwater resources as social-ecological systems

2.1. Conceptual framework for freshwater social-ecological systems (SES)

The freshwater social-ecological conceptual framework was developed through an extensive literature review (Vollmer et al., 2016),