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

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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.

Keywords: freshwater sustainability, water governance, stakeholder engagement, ecosystem services, freshwater ecosystems

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. 2014) 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 (Vorosmarty 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 (Martinez-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), two interdisciplinary scientific workshops held in December 2015 and July 2016, and consultations with stakeholders from the Pearl River and Mekong River basins in July and November 2016. It builds on Ostrom's (2009) general social-ecological systems framework by characterizing freshwater systems as dynamic social-ecological networks, with linkages and feedbacks that highlight human water uses, the effects of these uses on freshwater ecosystems and, importantly, the role that governance plays in the sustainable and equitable delivery of water-based services through the maintenance of functioning ecosystems (Fig. 1). It illustrates the different dimensions that need to be measured in order to understand how social, hydrologic and ecological systems interact. Watersheds provide a logical physical boundary for conceptualizing a freshwater SES, given that water moves through watersheds from higher to lower elevations and watersheds also include underground water movement and storage. Depending on data availability, the framework described here is scalable and can be applied to sub-basins or multiple adjoining basins (to account for inter-basin transfers) on up to national-level assessments and international transboundary basins.

Our conceptual framework for freshwater SESs consists of: Ecosystem Vitality, Ecosystem Services, Governance and Stakeholders (Fig. 1). Governance here refers to the "structures and processes by which people in societies make decisions and share power, creating the conditions for ordered rule and collective action, or institutions of social coordination" (Schultz et al. 2015, pg. 7369). This definition encompasses multiple tiers of governments, their formal rules and informal norms (e.g., community-established guidelines), non-governmental processes for collective action and decision-making and market mechanisms. Stakeholders are actors who depend on freshwater services from a basin or are involved in the decisions that affect these services. This includes individual citizens, community groups, municipalities, and corporations that have a *de facto* right to the benefits of water. Other stakeholders include entities such as non-governmental and international organizations that may not directly benefit from the ecosystem services in a particular location, but nonetheless have an interest in, and influence over, decisions that affect the basin. Stakeholders operate within the constraints of a governance system that affects their behavior but, in turn, stakeholders also may influence or shape the governance system by modifying rules or changing the composition of the system.

Ecosystem Vitality (Fig. 1) refers to the status and trends of the condition of freshwater ecosystems within a given basin, encompassing aquatic (including groundwater), riparian and terrestrial realms, including their biodiversity (species, communities) and abiotic components, as well as the biophysical processes affecting them. As mentioned above, freshwater ecosystems produce a range of ecosystem services and benefits to stakeholders (Fig. 1)—such as water capture, storage and provision, bioremediation of waste, hazard mitigation (e.g., flood control), food and raw materials, and cultural services such as spiritual and aesthetic experiences and recreation opportunities (Milcu et al. 2013). Critically, the condition of terrestrial and freshwater ecosystems in a basin affect the quantity, quality, location and timing of water-related ecosystem services (Baron et al., 2002; Brauman et al., 2007). Freshwater SESs are also affected by external biophysical stressors that may operate at scales much larger than the drainage basin (e.g. climate change affecting precipitation and extreme weather events), as well as social, economic and political factors emanating from outside the basin. Furthermore, water or water-dependent products can be imported or exported to beneficiaries within and outside of the watershed.

2.2 Identifying Indicators of Freshwater Health

The conceptual framework was developed specifically to serve as the basis for the selection of indicators to assess freshwater resource sustainability. To this end, indicators were selected in the context of three major components: Ecosystem Vitality, Ecosystem Services, and

Governance and Stakeholders (Tables 1-3). Each component has associated with it major indicators comprised of multiple sub-indicators; major indicators are described below while sub-indicators are defined in the Supplement. Selection of indicators was informed by whether empirical data are likely to exist, can be modeled, or can otherwise be collected efficiently and cost-effectively, (see Table A.1 for proposed metrics and local- and global-scale data sources for Ecosystem Vitality and Ecosystem Services, and the Supplementary Material for a survey instrument employed for Governance and Stakeholders).

2.2.1 Indicators for Ecosystem Vitality

Ecosystem Vitality aligns closely with existing indicators of river ecological health (e.g., Vugteveen et al., 2006). They are selected to provide a summary of water-relevant ecosystem processes and the capacity of freshwater ecosystems to provide services. Four major indicators are identified:

Water quantity measures changes in the stock and flow of water through the drainage basin and water-storage capacity. It captures the degree to which current flow conditions have shifted from historic natural flows and depletion in terrestrial and groundwater storage.

Water quality refers to the state of both surface and subsurface water sources within the basin. It pertains to the quality of water needed to maintain healthy and biodiverse aquatic ecosystems rather than for human use. The three most important sub-indicators of water quality are total nitrogen and total phosphorous, and—in surface waters—suspended solids. However, a host of additional water quality metrics may be influential depending on the context of the basin (UNEP 2008). These include salinity, dissolved oxygen, pH, electrical conductivity, total dissolved solids, coliforms, as well as pharmaceuticals and other contaminants.

Drainage basin condition captures the impacts of land-use change and river engineering on ecosystem processes and biodiversity, including habitat, which is sometimes identified as a separate category of ecosystem services (TEEB, 2011). It includes measures of physical modifications to rivers and wetlands such as dams and river channelization that can cause degradation of ecosystems, and changes in land cover and wetland extent, which affect infiltration and runoff rates as well as water quality.

Biodiversity highlights potential shifts in freshwater ecosystem functioning by measuring changes in the constituent biota, as they are integral components of freshwater ecosystems. The status and trends of biodiversity in a given basin signify ecosystem health, with declining populations of native species, and increasing populations of invasive and nuisance species, indicating a deteriorating ecosystem. The biodiversity indicator is comprised of presence and population sizes of aquatic and riparian species of concern (e.g., threatened species) as well as invasive and nuisance species.

2.2.2 Indicators for Ecosystem Services

The Ecosystem Services component focuses on the benefits delivered to stakeholders across a range of sectors. The major indicators follow well-established classifications and distinguish among provisioning, regulating, and cultural ecosystem services (MEA, 2005):

Provisioning measures the outputs from freshwater ecosystems that provide human benefits for a range of users such as the agricultural, municipal and industrial sectors and the environment. This includes water use for hydro- and thermal power generation and navigation. In addition to volumetric measures of water for consumption relative to demand, this indicator takes account of reliability of the water supply to meet demand, along with natural biomass production such as fisheries, fiber and wild food.

Regulation and support considers the aspects of freshwater ecosystems that either underpin provisioning services or reduce exposure to other hazards, such as water-associated diseases and flooding. This includes filtration and purification capacity affecting the quality of water needed to meet consumption demands across sectors, changes in soil and nutrient retention within the basin, and flood mitigation (provided upstream by reducing peak flows and/or downstream by absorbing floodwaters).

Cultural/aesthetic indicators measure the existence and experiential values of a freshwater system that are important to humans. These include conservation sites, sites with heritage, spiritual and cultural values, and the demand for water-based recreation opportunities.

2.2.3 Indicators for Governance & Stakeholders

We combined governance and stakeholders in the conceptual framework to form a single set of indicators, Governance & Stakeholders, because of the heavy reliance of each on the other and the tight feedback that connects them. Here, we focus on governance systems directly related to freshwater ecosystems rather than the broader social, economic or political context in which water governance lies. There is no single framework for measuring water governance, but we draw from common principles established by the OECD (2015), UNDP (Jacobson et al., 2013) and others (see Vollmer et al., 2016 for a review).

Enabling environment reflects the constraints and opportunities that are enshrined by policies, regulations, market mechanisms and social norms in governing and managing freshwater resources. It includes the extent to which typical water resource management functions (monitoring and coordination, planning and financing, developing and managing infrastructure, and resolving conflicts) are implemented through policies, institutions, management tools, financing and accounting for various users and uses. It also considers the coherence of existing rights to resource use, including how water, land and fishing rights are allocated, customary rights (including land tenure), and the degree to which these work in conjunction with formalized rights. Availability of different management instruments, as well as the capacity of skilled professionals working in water resource management fields, is also captured here.

Stakeholder engagement is a measure of stakeholder interactions and the degree of transparency and accountability that govern these interactions. It measures the access stakeholders have to information and data on local water resources in order to inform decision-making as well as the extent to which stakeholders have a voice within the cycle of policy, planning and decision-making.

Vision and adaptive governance includes the extent to which stakeholders engage in comprehensive strategic planning at the basin or sub-basin scale, the capacity to adapt to new information and changing conditions, and the existence of monitoring mechanisms to measure progress toward social and environmental objectives.

Effectiveness measures the degree to which laws are upheld and agreements are enforced, the distribution of water-related benefits, and the presence of water-related conflict.

3. Methods

3.1 Measurement and Aggregation of the Indicators

Sub-indicator values for Ecosystem Vitality and Ecosystem Services are generally based on spatially distributed, monitored or modeled data across sub-basins or administrative jurisdictions (e.g., county or municipality). Spatial aggregation for a basin-level score is either embedded in the indicator calculation process, such as for the Dendritic Connectivity Index (Cote et al. 2009), which measures fragmentation of the overall stream network, or it is carried out as an extra step using additional factors such as area, stream length, or discharge to determine proportional weights for the values calculated for individual sub-basins or monitoring sites. The survey instrument for the Governance & Stakeholders indicators involves approximately 50 questions, organized into 12 modules corresponding to our proposed sub-indicators, and includes metadata on location within the basin as well as sectoral affiliation. Although responses are averaged for the group, the disaggregated data allow for within sample comparative analysis, to identify potential factions based on geographic location and/or affiliation. A summary of the specific methods used for each sub-indicator is available in the Supplementary material, and full documentation can also be found at freshwaterhealthindex.org/user-manual.

Once sub-indicator values at the basin-scale were estimated, they were normalized to a common non-dimensional scale of 0-100, where higher values denoted a positive assessment of that dimension in regard to sustainable freshwater health. Sub-indicators with a negative connotation, such as “Bank modification” and “Water-Related Conflict”, thus use an inverted scale. These non-dimensional sub-indicator values were then aggregated via a geometric mean to provide an overall value for each major indicator. The major indicators were further aggregated (again using the geometric mean) to provide an index value for each component. The indices were not further aggregated across the three components since demonstrating the values for the three main components separately can highlight the source of the greatest problems or the most prominent factors contributing to sustainability. High index values across all three components are indicative of a sustainable freshwater ecosystem. A low value for a component, a major indicator or a sub-indicator highlights an area for improvement. For instance, a low value for the Ecosystem Vitality index can serve as an early warning signal that ecosystems cannot sustainably provide water-based ecosystem services or maintain biodiversity; a low value for the Ecosystems Services index signals that societal water needs are not being met; or a low value for the Governance & Stakeholders index can elucidate processes that stakeholders can change in order to realize improvements in Ecosystem Vitality and Ecosystem Services.

Prior to aggregation, weights can be applied to denote greater or lesser importance of the role of each indicator for assessing freshwater health in the basin. As we demonstrate with the application in the Dongjiang basin, this weighting exercise provides not only a quantitative input to the aggregation of sub-indicators, but also reveals stakeholders' preferences. There are a variety of methods for assigning weights including, but not limited to, expert elicitation (Morgan, 2014), the Delphi method (Linstone & Turoff, 1975), or the Analytic Hierarchy Process (AHP) (Saaty, 2005). We apply the AHP method as it is well-suited to our hierarchical indicators and allows a large number of stakeholders to provide input, recognizing that the relative importance of Ecosystem Services and Governance & Stakeholders indicators is a subjective matter.

3.2 Application in the Dongjiang River Basin

We illustrate the application of the Freshwater Health Index through a case study of the Dongjiang basin, which is the eastern tributary of the Pearl River)—Zhujiang)—in southern China (Fig. 2). The case study served two main objectives. First, it subjected our framework to the real-world challenge of providing decision-relevant insights, by working directly with stakeholder groups in the basin. Second, it tested the ability of our framework to assimilate suitable metrics based on available local and global datasets. With an annual average discharge of 739 m^3/s and basin area of 35,340 km^2, the Dongjiang is the smallest tributary of the three main rivers comprising the Pearl River system. Despite its size, the Dongjiang is the primary water source for more than 40 million residents, including the world's largest urban agglomeration. Beginning in the late 1950s, dams were constructed to provide flood control and hydropower but, as the delta population grew and urbanized, water allocation and quality have emerged as top priorities. Socioeconomically, there is a substantial disparity between the rural upstream communities and the urban areas (including Shenzhen and Hong Kong) in the delta—per capita GDP is at least 10 times greater downstream. This provides an impetus to maximize the productive use of land upstream through mining, intensified agriculture and industrial relocation, which could bring short-term economic development but threaten water-related ecosystem services.

Over a period of approximately 12 months, we worked with local institutions and technical experts in Guangdong Province to adapt and calculate the sub-indicators. Additionally, we convened two stakeholder workshops, each involving approximately 40 participants from local, provincial and national government agencies, regional bodies (the Dongjiang River Basin Authority and the Pearl River Water Resource Commission) as well as the private, non-governmental organization (NGO) and academic sectors. At these workshops, the survey instruments to populate and weight the Governance & Stakeholders indicators were implemented. The process and preliminary results of the Freshwater Health Index were discussed in follow-up meetings to obtain critical feedback and insights into policy relevance and potential management responses.

For the Dongjiang basin, quantitative information to evaluate the indicators primarily came from in situ monitored water quality and discharge data sets, provincial statistical yearbooks, land cover maps, the China Biodiversity Red List, modeled hydrological data using a Variable Infiltration Capacity (VIC) Land Surface model, and a sediment loss and erosion model (Lai et al., 2016). These were used to calculate indicator values for Ecosystem Vitality and Ecosystem Services. Values for Governance & Stakeholders indicators were determined qualitatively and were elicited via a 49-question survey using a Likert-type 5-point scale administered in Chinese to workshop participants. Survey responses were averaged and normalized to give indicator scores on a 0-100 scale. We also elicited major and sub-indicator weights from stakeholders with a two-level Analytic Hierarchy Process for the Ecosystem Services and Governance & Stakeholders components, calculated using a balanced scale in the BPMSG AHP online system (Goepel, 2013), a web-based tool for using the AHP in group decision-making. In this context, weights convey the importance stakeholders place on aspects of governance and water use in the basin. The Ecosystem Vitality indicators were not weighted (equivalent to equal weighting in the geometric mean aggregation) since their relative importance to freshwater ecosystems is most often an objective matter that should be informed through empirical, rather than subjective, means.

4. Results & Discussion

4.1 Weights and Indicator Scores for Dongjiang Basin

The weights and aggregate scores for each sub- and major indicator for the Dongjiang basin are summarized in Figure 3 (see also Table S2). Scores are assigned a color based on the 0-100 gradient, and the size of each wedge reflects its relative weight determined through the AHP weighting exercise. Deviation from Natural Flow and Land Cover Naturalness under Ecosystem Vitality are represented spatially in Figure 4. All major indicators were evaluated, except for

Cultural services for which no suitable data existed; it is highlighted here as a data gap. While it was included in the weighting exercise in order to assess stakeholders' perception of its importance, Cultural services were omitted from the aggregated score for Ecosystem Services by rescaling the weights for the Provisioning and Regulating major indicators to sum to 1.0. Indicator values ranged from 41 to 76 (out of 100) across all components, with seven indicators receiving scores of 50 or less.

Within the Ecosystem Services component, Provisioning services were weighted the highest at 0.61, followed by Regulating services, which were weighted slightly less than half as important as Provisioning services, and then Cultural services were weighted less than half as important again. Under the Governance & Stakeholders component, Effectiveness was weighted the highest, followed by Enabling Environment, Vision & Adaptive Governance, and finally Stakeholder Engagement. These were all spaced evenly apart from the highest weight at 0.28 (for Effectiveness) to the lowest weight at 0.11 (Stakeholder Engagement). Application of the weights did not influence aggregated scores substantially. For the Governance & Stakeholders indicator scores, weighted aggregation of sub-indicators to major indicator values changed less than two points in either direction, but the major indicator aggregated score was the same (56) whether weighted or unweighted.

4.2 Interpretation of Scores for the Basin

Results for the Dongjiang basin generally met our expectations, but also highlighted issues for further analysis or data collection. The summary scores suggest that human needs are currently being met fairly well (Ecosystem Services score of 82) but at the expense of the region's ecology (Ecosystem Vitality—60), and the current governance structure may need to be reformed (score of 56) to address this imbalance and handle future challenges like population growth and climate change. While it may appear counterintuitive to have high Ecosystem Service scores but lower scores for other components, we posit two interpretations. The first is that there are often tradeoffs between maintaining elements of Ecosystem Vitality and maximizing certain services such as water provision or flood regulation, thus some negative correlation is expected. For example, given the high degree of regulation of surface water in the basin, the low score for Water Quantity under Ecosystem Vitality, which measures shifts in the seasonal flow pattern, is not surprising (nor are the low scores for Bank Modification and Flow Connectivity). Second, there is likely a time lag and thresholds before we might observe positive correlations among sub-indicators—this can be explored through more historical analysis but requires further research and long-term monitoring of the governance sub-indicators.

We were unable to obtain monitoring data for groundwater, the other component of Water Quantity within Ecosystem Vitality. While stakeholders primarily rely on surface water allocation to meet their needs, groundwater abstraction is increasingly occurring both for industrial production of bottled water and to meet municipal demand (Yang et al., 2016). This growing stress on water allocation is reflected in the moderately low score (60) for Provisioning and suggests that groundwater monitoring is a key knowledge gap, given that it could be increasingly important in meeting water demand. It is also worth noting that current water allocations account for environmental flows (Lee and Moss, 2014), but these minimum flow requirements are not based on ecological requirements or ecohydrological-relationships and are instead intended to prevent sea water intrusion from the Pearl River delta.

Water Quality received the highest weight among Regulation and Support services (which include flood, sediment and water-associated disease regulation), reflecting stakeholders' concerns with deteriorating water quality in the basin. This is something that has received significant attention from local governments (Lee and Moss, 2014) with the establishment of additional monitoring stations and the introduction of 'polluter pays' systems. And while the Water Quality indicator suggested moderate health for human consumption purposes (72), fecal coliform levels were regularly higher than the threshold (China's Class II standard of 2000/L) at all four monitoring stations as a result of unregulated discharges of municipal waste. With the growing industrialization of the mid-stream sections and the downstream decline in freshwater biodiversity that is evident already (Zhang et al 2010), water quality monitoring requires further attention.

This points to another knowledge gap: biomonitoring and linking the biological state of the river system to resource management concerns. In a one-off study of aquatic macroinvertebrate diversity along the Dongjiang, Zhang et al. (2010) detected a downstream decline in ecosystem health associated with increases in nutrient leading and the extent of impermeable surface in the surrounding landscape. Zhang et al. (2015) previously suggested that biological diversity in the Dongjiang River declined with the construction of the major reservoirs in the 1960s and early 1970s, though they relied on hydrologic alteration measures rather than species data. While we did calculate a Biodiversity index (73), which came out as the highest value in the Ecosystem Vitality component, we relied on spatially and temporally coarse data from the IUCN and Chinese Red Lists. Regular local species monitoring has been proposed (Jia & Chen, 2013; Yang et al., 2014) as a way to help synthesize cumulative impacts of changes to water quantity, water quality and basin condition, but until now this information is not widely available and has not been used by resource managers or other basin stakeholders to inform management in the basin. Still, our Ecosystem Vitality indicators and sub-indicators tracked well with previous assessments of ecological health for the basin (Wang et al., 2011; Jiang et al., 2015), which note channelization, fragmentation and flow modification as being areas of greatest concern in an otherwise ecologically healthy basin.

Overall, the Governance & Stakeholders component included the lowest performing indicators—no sub-indicator scored above 60—suggesting that this should be a priority area of concern for the Dongjiang basin. We do not advise that governance scores should be improved for their own sake—after all, Ecosystem Services scores are presently high in the basin. Rather, the low governance scores offer insight into areas that may require attention as the basin undergoes changes, whether from population growth, economic restructuring, or climate change. New institutional arrangements, such as upstream compensation for environmental stewardship, are being discussed in the basin, but underlying governance problems may need to be addressed before instituting new mechanisms. The weighting revealed that stakeholders consider outcomes (measured as "Effectiveness") twice as important as Stakeholder Engagement. Therefore, the low scores for Information Access (50) and Engagement in Decision-making (44) are likely of secondary concern when compared to Water-related Conflict (48). The poor score for Water-related Conflict reflects increasing tension over water quantity and quality in the basin (Lee and Moss, 2014).

Finally, the indicator scores for Flood Regulation and Sediment Regulation highlight the changing character of this river system and the trade-offs associated with river infrastructure development. While floods were historically a frequent natural disaster in the basin (Liu et al. 2012), channelization of the downstream segments and reservoir storage have greatly reduced floods as a major threat. However, these modifications have impacted the sediment dynamics of the system. The Basin Condition score (62) reflects this modification, but suggests that the basin has only seen moderate impacts of the modification of its stream network. The bank modification is concentrated at the downstream end of the river basin; however, the main reservoirs also exert a strong influence on sedimentation; sediment flow at the outlet has more than halved between 1955 and 2005 based on observed records (Dai et al. 2008), which affects the amount of nutrients reaching the estuary as well as brackish water intrusion upstream. Furthermore, increases in urbanization in the region over recent years has led to increased riverbed dredging to meet demand for gravel and related construction material. This has been associated with a fall in river bed level, measured at a downstream gauge (Boluo), by 1-1.5 m between 1995-2002 (Liu et al., 2012) and an expected weakening of the flood levees. Despite these changes and potential risks, empirical data on sediment loss were not easily accessible, and we relied on modeled data to estimate sediment regulation. It is essential to set up a system for regular monitoring of dredging and its consequences for levee stability.

4.3 Stakeholder Engagement under the Framework

This initial application of the Freshwater Health Index revealed useful information about the Dongjiang basin, but also about the framework and its generalizability. It represented the first comprehensive assessment of the Dongjiang River basin within a social-ecological framework—previous assessments focused on either water quantity or water quality issues separately, and did not address issues such as biodiversity, land use, ecosystem services, or governance. In this regard, the Freshwater Health Index provided a framework for evaluating these various dimensions concurrently and, more importantly, a framework upon which to base discussions of the relationships and interactions among these variables within the Dongjiang basin. The concept of ecosystem services was new to many workshop participants, but it could be succinctly illustrated by reference to the protected areas that surround the basin's three main reservoirs—these mountainous areas maintain mostly forested land cover in order to safeguard water supplies, but at the same time provide recreational amenities within a 2-hour drive of the populous urban centers of the Pearl River Delta.

This comprehensive framework proved useful in facilitating discussion among traditionally stove piped water resource management sectors. The Pearl River Water Resource Commission (PRWRC), under the Ministry of Water Resources, was established specifically to help manage regional water issues. In practice, however, water resource management is decentralized, so the PRWRC defers to provincial and municipal governments on most matters concerning the Dongjiang (Yang et al., 2016). The Dongjiang River Basin Authority was created by the Guangdong Province Bureau of Water Resources and is concerned primarily with water quantity and allocation in the basin, but it was not designed to be a convener of the lower level municipal and county offices or to oversee all aspects of freshwater health (Lee and Moss, 2014). Therefore, the Freshwater Health Index assessment process and workshops provided an impetus to convene these public agencies, together with relevant industries, NGOs, and research institutions, to share information and discuss issues of concern in the Dongjiang basin. Based on an ex-post survey we conducted, stakeholders exhibited a strong interest in continuing to use the Freshwater Health Index, to evaluate scenarios for future change and to use as a monitoring tool. Representing the information by sub-basins preserved information; however, most end-users did not know how to interpret results at this finer spatial scale and preferred spatial aggregation of sub-indicators along administrative jurisdictions. This pointed to another value of the framework: bringing together the lower level administrative representatives (municipalities and counties) to consider freshwater issues from a basin perspective.

Despite not substantially influencing aggregated indicator scores, the weighting exercise and results did provide valuable insight into the general priorities or awareness stakeholders in the basin have. For example, sediment regulation received a very low weight, despite the fact that the basin's reservoirs are protected by restricted forest zones. This suggests that stakeholders are not generally aware of this "free" service or do not associate it with a healthy ecosystem, whereas the regulating services with clearer human-environment interactions (water quality, flooding, disease) were all weighted at least three times higher. We do not advise "correcting" weights, but such an example signals an opportunity to increase public awareness about certain topics illuminated by the Freshwater Health Index. Stakeholder engagement received the lowest weight among the Governance & Stakeholders major indicators, and this mirrored the feedback workshop participants provided: that water resource management is not an open process in China, and that the naturally subjective dimensions of "good governance" are not universal in terms of their importance. Finally, the weighting exercise allowed us to analyze differences in preferences based on location (upstream versus downstream) and sectoral affiliation. Even considering the small sample size ($n = 32$), we anticipated being able to detect statistically significant differences in preferences, but found none. This suggests areas of common ground for stakeholders in the Dongjiang basin, but is worth investigating with a larger sample as well.

4.4 Extensions of the Freshwater Health Index

The Freshwater Health Index is intended primarily for within-basin comparisons over time, or via scenarios, rather than across basins, to allow for basin-specific flexibility in terms of data inputs and measurement methods. Within a basin, historical data analysis and scenario modeling can help establish the sensitivity of indicator values. Such sensitivity analyses are identified as a next step to gauge whether improvements to freshwater sustainability are occurring as rapidly as expected in response to management actions, or whether a modest decline should be of major concern requiring prompt action. It is in the examination and response to these relative shifts that the index values have the greatest utility, rather than the absolute component values of the Freshwater Health Index. More research will be needed to understand how, and under what circumstances, changes in sub-indicators are linked. A single snapshot of the FHI cannot reveal these linkages, but additional historical analysis (where data are sufficient) and quantitative modeling should both help identify issues such as time lags, thresholds, and sensitivity to changes. This, in turn, would help users understand links between ecosystem health and service delivery, and to identify tradeoffs before they occur.

The FHI indicators and suggested metrics are designed to make use of existing data, but since data availability varies considerably around the world, it is also useful in highlighting data gaps and thus setting priorities for data collection or organization. This highlights the importance of having a conceptual framework guiding indicator selection, as opposed to biasing an index toward existing data or unsuitable proxies—a full understanding of freshwater health will likely require additional efforts in data collection. Cultural services were the most notable gap for the Dongjiang basin, though this was not unexpected as cultural ecosystem services are less commonly evaluated than material services, and more difficult to create proxies from routinely collected data (Chan et al., 2012). Given the relatively high weight stakeholders placed on Conservation and Cultural Heritage, despite not having existing data on its condition, work is now underway to develop a locally-relevant metric that can be re-evaluated over time. Stakeholders also expressed interest in providing more local data to improve the spatial resolution of disaggregated sub-indicator evaluations and ensure that data were all covering the same time period. Without a unifying framework such as the Freshwater Health Index there was little incentive to share these data throughout the basin.

The interpretation of the scores involves a degree of subjective judgment. Values toward the extremes of 0 and 100 are understood as being poor or excellent, respectively, but end-users may interpret intermediate scores differently. For example, is a Biodiversity score of 73 any less an imperative for improvement than an Enabling Environment score of 57? Selection of weights gives insights into these priorities, with higher weights conferring greater importance of the associated indicator to freshwater sustainability. Certain indicators refer to established thresholds based on human health or other criteria, but in the absence of existing regulatory requirements, and because diverse indicators are aggregated within a major indicator and a component, even these must ultimately be transformed into categories that range from poor to excellent. We suggest thresholds of 60, below which should be considered as "low" freshwater health and high priority areas for improvement, 60-79 as "moderate" freshwater health and also areas for improved management, and 80, above which should be considered "good" health. Scores can be best used to compare the status of a basin over time, or to compare values under different scenarios such as water management actions or environmental changes. However, as presented here, they can also point to areas for potential improvement.

Stakeholders in the Dongjiang River basin expressed a strong interest in exploring future changes via scenarios. These scenarios include future economic development—increased urbanization and industrial relocation to upstream areas of Huizhou and Heyuan—as well as climate change, which may create more frequent extreme events (floods and droughts) in the basin (Yang et al., 2016). Thus, a next step in the basin would be to develop detailed scenarios with stakeholders and then model these scenarios with a suite of hydrologic, quality, hydraulic, soil loss, and allocation models to evaluate changes in specific Ecosystem Vitality and Ecosystem Services indicators relative to this initial baseline assessment. Not all indicators can be quantitatively modeled using this approach, but for those that can, this step will also help stakeholders identify undesirable trade-offs and possible synergies, and begin setting targets for the basin's health. And by repeating the assessment over time (e.g., 3-5 years), the Index allows users to test hypotheses about how improved water governance leads to better outcomes as measured in Ecosystem Services and Ecosystem Vitality. Using this common framework across a variety of basins, it is even possible to develop a knowledge base over time on the empirical relationship between changes in governance, ecosystems and benefits.

5. Conclusion

The social-ecological framework presented here, and the indicators derived from it, take account of the interplay between governance, stakeholders, freshwater ecosystems and the ecosystem services they provide. This reflects the fact that each of these components must be assessed, monitored and managed, with equal consideration, to achieve a realistic and pragmatic understanding of freshwater sustainability and the way it can be achieved. The Freshwater Health Index framework and its accompanying indicators are oriented toward management and stakeholder engagement, and they make a significant contribution by providing a systematic, evidence-based quantitative tool that supports the integrative social and ecological nature of fresh waters at the basin level. The Freshwater Health Index is flexible in that it can be adapted to a wide range of contexts and user needs, providing a much needed implementation tool for operationalizing IWRM. This paper has shown one such demonstration in the Dongjiang basin, where local anthropogenic pressures are high and integrated management is currently weak.

The Index is intended to be used iteratively, testing scenarios and informing data collection and monitoring over time. With the aid of hydrologic and ecosystem service models, this can be used to analyze proposed management plans or uncertain future scenarios, thereby assisting in decision-making and policy development. By explicitly juxtaposing the social and ecological dimensions of the problem within a consistent framework, the human need for water is linked with the ability of freshwater ecosystems to meet those needs without compromising habitat integrity or threatening biodiversity. The Index also highlights the vital, yet much neglected, role of governance in safeguarding the delivery of these services in an equitable and sustainable manner. Moreover, this framework is explicitly designed to support concerted international efforts such as the UN Sustainable Development Goals (SDGs) (United Nations 2015) and the International Panel on Biodiversity and Ecosystem Services (Diaz et al 2015), which recognize the interlinked social and ecological dimensions of sustainable ecosystem service provision.

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Table 1. Ecosystem Vitality indicators

Major indicators	Sub-indicators
Water quantity	Deviation from natural flow regime
	Groundwater storage depletion
Water quality	Suspended solids in surface water[1]
	Total nitrogen in surface and groundwater[1]
	Total phosphorous in surface and groundwater[1]
	Indicators of major concern[2]
Drainage-basin condition	Percent of channel modification (bank modification)
	Dendritic connectivity index (flow connectivity)
	Land cover naturalness[3]
Biodiversity	Changes in number (i.e. species number) and population size of species of concern
	Changes in number and population size of invasive and nuisance species

1. Deviation of concentration from environmental benchmark related to local historic natural conditions.
2. Optional; depends on local conditions and could include salinity, dissolved oxygen, pH, electrical conductivity, total dissolved solids, heavy metals and coliforms, as well as pharmaceuticals and other contaminants.
3. Naturalness here is measured on a gradient from completely natural (e.g., primary forest) to completely artificial (e.g., urban areas).

Table 2. Ecosystem Services indicators

Major indicators	Sub-indicators
Provisioning	Water supply reliability relative to demand
	Biomass for consumption[1]
Regulation and support	Sediment regulation
	Deviation of water quality metrics from benchmarks[2]
	Flood regulation
	Exposure to water-associated diseases
Cultural/aesthetic	Conservation/Cultural Heritage sites
	Recreation

1. Optional; include depending on local conditions
2. Refers to ability of the freshwater ecosystem to deliver water of the expected water-quality standards for different sectors.

Table 3. Governance & Stakeholders indicators

Major indicators	Sub-indicators
Enabling environment	Water resource management Rights to resource use Incentives and regulations Financial capacity Technical capacity
Stakeholder engagement	Information access and knowledge Engagement in decision-making processes
Vision and adaptive governance	Strategic planning and adaptive governance Monitoring and learning mechanisms
Effectiveness	Enforcement and compliance Distribution of benefits from ecosystem services Water-related conflict

Figure 1. Conceptual framework for freshwater SESs comprised of Governance and Stakeholders, Ecosystem Vitality and Ecosystem Services. Stakeholders set and adapt rules within governance and market systems and also respond to them. Within the constraints and rules set by water governance, stakeholders modify ecosystems through land-use change or conservation in order to exploit or manage freshwater ecosystems, and also by developing infrastructure and technology to access water-based ecosystem services. Modifications to ecosystems and water withdrawals can alter the flow regime and water quality and thereby affect delivery of ecosystem services to beneficiaries. In basins where there are competing water needs, tradeoffs become apparent and may necessitate an adjustment to governance mechanisms that can trigger changes in markets. Freshwater SESs are also impacted by external biophysical influences such as drought or climate change that affect ecosystem service delivery that can feed back to affect governance. Basins are also embedded within a broader social, political and economic context that can influence governance systems and thus management of fresh waters. While we recognize that water and water-based goods and services may also be imported into or exported from a basin, our focus is primarily on interactions within the basin.

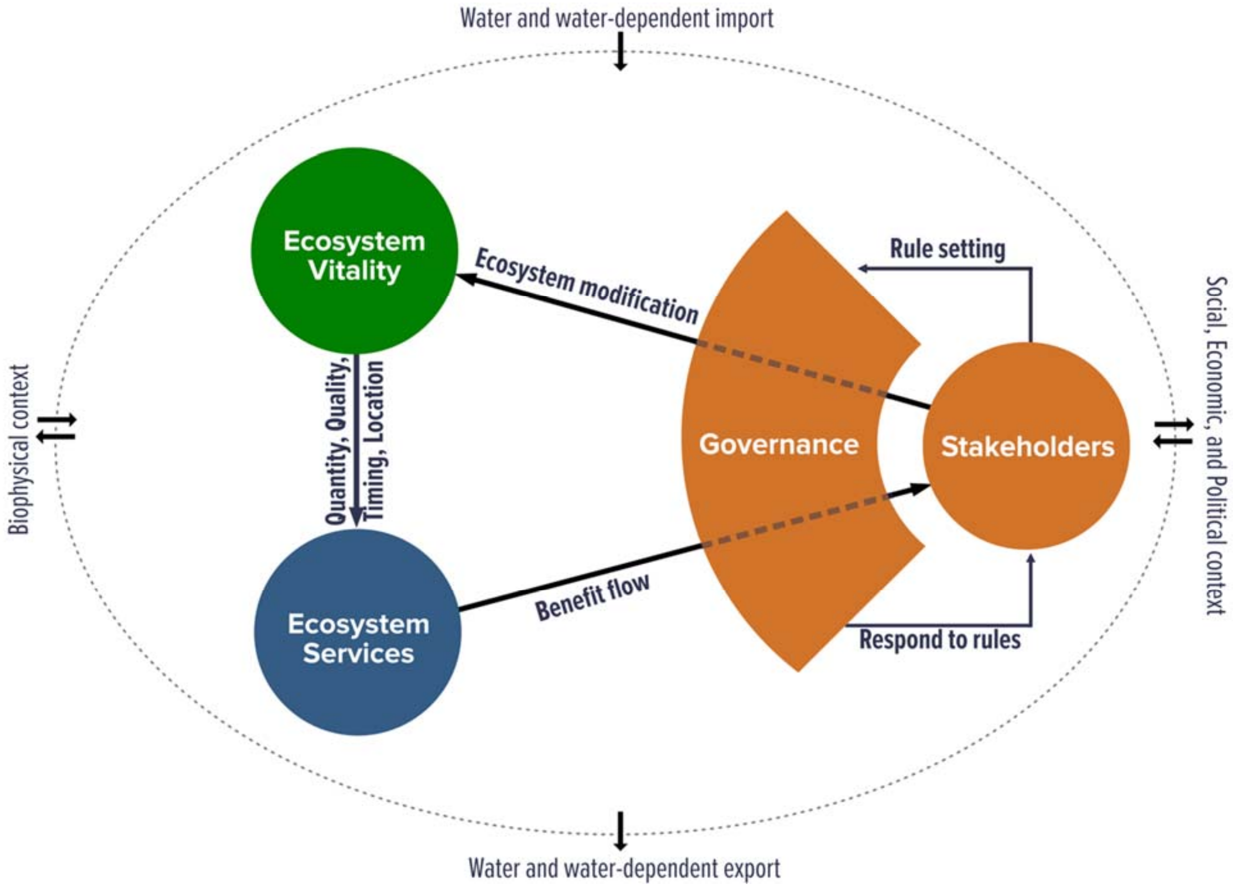

Water and water-dependent import
Ecosystem Vitality
Ecosystem modification
Rule setting
Biophysical context
Quantity, Quality, Timing, Location
Governance
Stakeholders
Social, Economic, and Political context
Ecosystem Services
Benefit flow
Respond to rules
Water and water-dependent export

Figure 2. Dongjiang basin (shaded) in southern China. Major municipalities are highlighted in bold text and demarcated with dashed lines. Reservoirs are labeled in italics.

Figure 3. Summary results for the Dongjiang River Basin. Component scores are noted numerically in the center, color gradient depicts scores for each major and sub-indicator, and the size of the wedge depicts the weight each (sub) indicator was assigned.

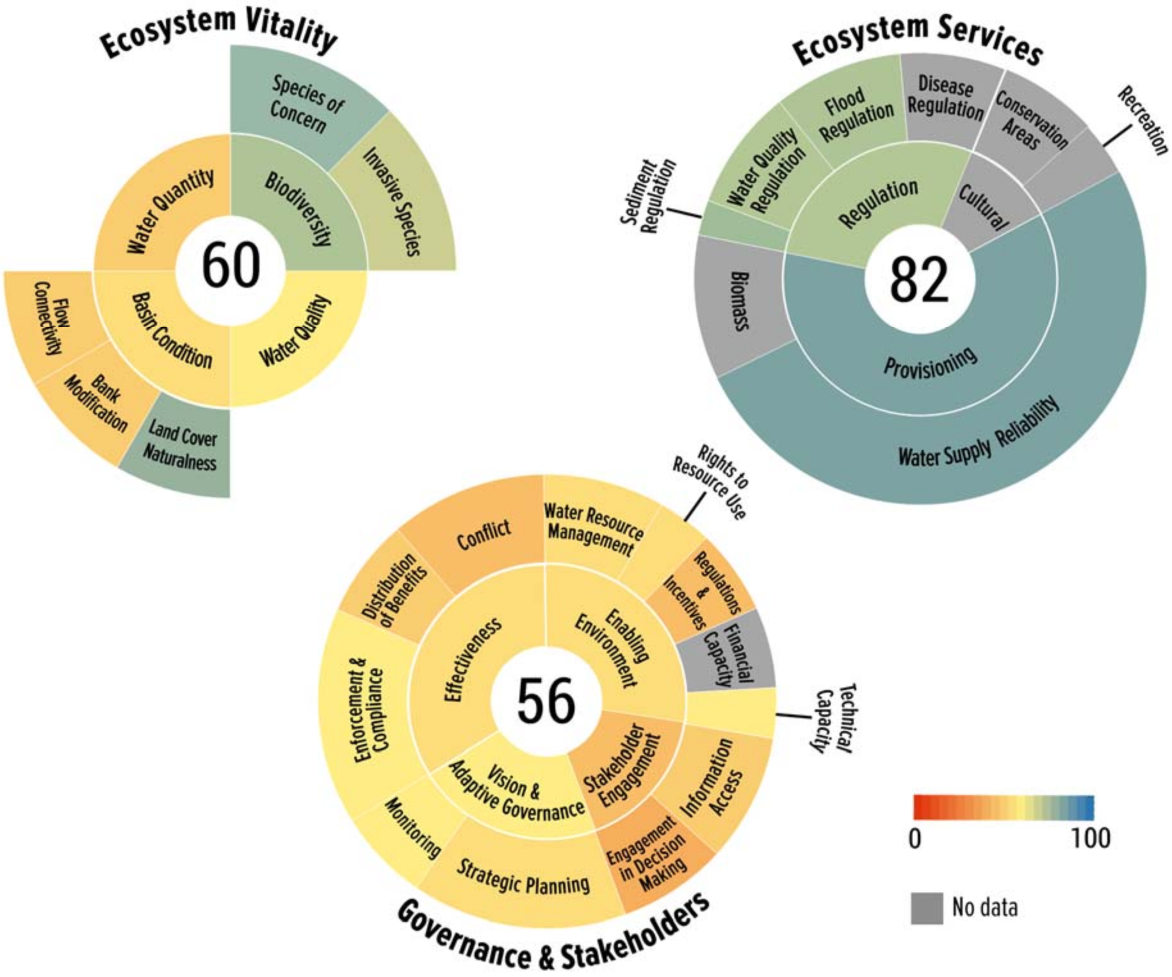
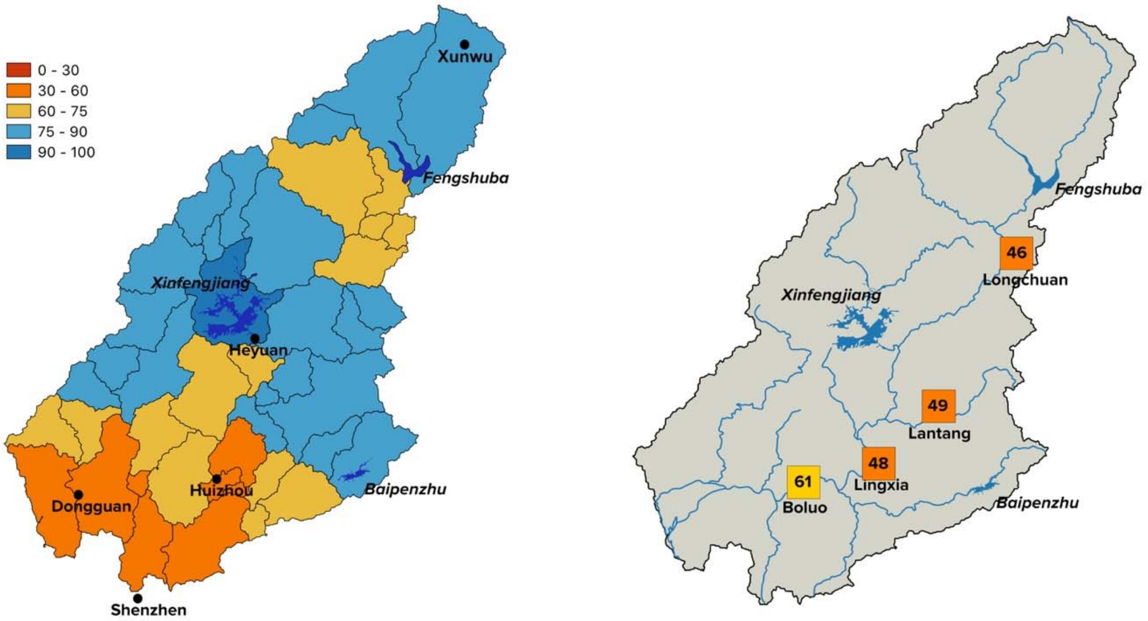


Figure 4. Spatial disaggregation of scores for Land Cover Naturalness (left, at sub-basin scale) and Deviation from Natural Flow (right, from monitoring stations). Mapping these indicators helps reveal variability within the basin, to better understand what drives scores and to set management priorities. Values are mapped according to the type of data input, and presented at either a sub-basin scale or as point data, using the same 0-100 scale where higher scores relate to better performance.



Text S1. Freshwater Health Index: Methods

The sections below provide an overview of the calculation process for indicators used in the manuscript and is derived from the ‘Freshwater Health Index user manual v1.1’. The authors encourage readers interested in detailed description of the methods as well as explanation of data sources and sample questionnaires to refer to the user manual (available at: www.freshwaterhealthindex.org)

All indicators are scaled in range 0-100.

1. Ecosystem Vitality Indicators

1.1 Water Quantity

Selected sub-indicators are intended to capture the change in stock and flows of water above and below surface. In stream/river dominated systems, the deviation from natural flow (DvNF) can be captured using the Amended Annual Proportion of Flow Deviation index (Gehrke et al. 1995, Gippel et al. 2011):

$$AAPFD = \sum_{j=1}^{p} \frac{\sqrt[2]{\sum_{i=1}^{12}\left[\frac{m_i-n_i}{\bar{n}_i}\right]^2}}{p} \qquad (1)$$

where, m_i is monthly flow data accruing to current condition, n_i is modeled natural flow for the same period. p is the number of years and $\bar{n}_i$ is mean reference flow for month i across p years (Note: in ephemeral streams, this should be changed to incorporate annual average flow to avoid extremely large values).

Values are normalized to a 0-100 scale using thresholds reported in Gehrke et al. (1995):

$$DvNF = \begin{cases} 100 - 100 \times AAPFD & \text{for } 0 \le AAPFD < 0.3 \\ 85 - 50 \times AAPFD & \text{for } 0.3 \le AAPFD < 0.5 \\ 80 - 20 \times AAPFD & \text{for } 0.5 \le AAPFD < 2 \\ 50 - 10 \times AAPFD & \text{for } 2 \le AAPFD < 5 \\ 0 & \text{for } AAPFD \ge 5 \end{cases}$$

(2)

1.2 Water Quality

Water quality for the natural environment considers at least 4 parameters: Total Suspended Solids (TSS), Total Nitrogen (TN), Total Phosphorus (TP) time series and concentrations of other pollutants of interest. These are combined using a modified version of the CCMW Water Quality Index (Saffran, Cash, and Hallard 2001). Thresholds required for each parameter are either derived from local environmental guidelines or literature. The steps of the calculation are:

a) Calculate ‘Scope’

$$\mathrm{F_1} = \left(\frac{\text{Number of failed parameters}}{\text{Total number of paramters}}\right) \times 100$$

(3)

b) Calculate ‘Frequency & Magnitude’

For each test [i] performed for each parameter, excursion beyond threshold for failed tests is calculated as:

$$\mathrm{Ex_i} = \left(\frac{\text{Failed test value}_\mathrm{i}}{\text{Threshold}_\mathrm{i}}\right) - 1 \qquad (4)$$

Or,

$$\mathrm{Ex_i} = \left(\frac{\text{Threshold}_\mathrm{i}}{\text{Failed test value}_\mathrm{i}}\right) - 1 \qquad (5)$$

Depending if value must not exceed or fall below the threshold. The values are converted to a scale 0-100 using the following steps:

$$\mathrm{nse} = \frac{\sum_{\mathrm{i}=0}^{\mathrm{n}} \mathrm{Ex_i}}{\text{Total number of tests}} \qquad (6)$$

$$\mathrm{F_3} = \left(\frac{\mathrm{nse}}{\mathrm{nse}+1}\right) \times 100 \qquad (7)$$

c) The F1 and F3 are combined:

$$WQI = 100 - \sqrt{F_1 \times F_3} \qquad (8)$$

1.3 Drainage basin condition

The sub-indicators under this attempt to account for state of the surface waterbodies as well as landcover on freshwater health. Some of the indicators considered are:

a) *Flow connectivity*, i.e. Longitudinal connectivity of stream network using Dendritic Connectivity Index (DCI)

Proposed by Cote et al. (2009), for a stream network fragmented by (n-1) impassable barriers, DCI for potamodromous and diadromous fish species are calculated as:

$$DCIp = \sum_{i=1}^{n} \frac{l_i^2}{L^2} \tag{9}$$

$$DCId = \frac{l_0}{L} \tag{10}$$

where, L is the total length of the river, l_i is the length of i^{th} fragment, and l_0 is the length of fragment closest to the mouth of the river system.

b) *Bank modification,* i.e. Lateral connectivity of stream network using percent of channel modification (pCM)

For each sub-basin, based on location of levees, dykes, channelization, clearance of instream obstructions to navigation, reservoir extent etc., the percentage length affected can be calculated (0 for near-natural, 1 for fully channelized). Scores for [i] sub-basins are combined using:

$$pCM = \left(1 - \frac{\sum_{i=1}^{n} l_i pCM_i}{L}\right) * 100 \tag{11}$$

where, L is the river network length, l_i is the length of the river fragment in *i*th sub-basin.

c) Amount of human-induced transformation present in land cover (LCN)

A Degree of Naturalness classification matrix is applied to each land-cover/land use (LULC) category available from the LULC map of the basin. The proposed weighting for "naturalness" in the matrix should include ranges of values to help highlight transitions from "natural" to "transformed" systems, i.e., from forests and wetlands to cultivated lands or from cultivated lands to urban areas – and is prepared/refined with help of local expert opinion.

The weights for each LULC type are combined using area covered by each LULC type as multiplier.

1.4 Biodiversity

The biodiversity indicator is the geometric mean of two sub-indicators: species of concern, and invasive and nuisance species.

Species of concern (ISC_i) has three components (1) the proportion of threatened freshwater species ($I_{TE,i}$), (2) change in the number of species of concern (ΔSC_i), and (3) average population trend across all species of concern (PT_i). These three parameters are then combined to give an overall index for the status and change in species of concern.

$$ISC_i = min\left\{ISC_{i-1} \sqrt[3]{I_{TE,i} \times \Delta SC_i \times PT_i}\, , 100\right\} \tag{12}$$

Due to data availability constraints, only $I_{TE,i}$ is calculated and ΔSC_i or PT_i were set to equal 1 for the calculation of ISC_i.

For species of concern the proportion of threatened freshwater species ($I_{TE,i}$) is calculated by determining the weighted proportion of freshwater species either as critically endangered (CR), endangered (EN), or vulnerable (VU) against the total number of species assessed (using IUCN Red list classification); calculated as:

$$I_{TE,i} = 1 - \frac{w_{CR}n_{CR,i} + w_{EN}n_{EN,i} + w_{VU}n_{VU,i} + \sum_j w_j n_{j,i}}{(w_{CR}n_{CR,i} + w_{EN}n_{EN,i} + w_{VU}n_{VU,i} + \sum_j w_j n_{j,i} + w_{NotT}n_{NotT})} \tag{13}$$

where $n_{CR,i}$, $n_{EN,i}$, and $n_{VU,i}$ are the number of species listed as CR, EN, or VU under the IUCN Red List categories and criteria at time $t = i$, respectively, $n_{j,i}$ is the number of species classified in an endangered or threatened category at the national or provincial level at time *i* (e.g., for regions that classify species as “endangered” or “threatened”, *j*=1 refers to the endangered category and *j*=2 refers to the threatened category), n_{NotT} refers to the remaining assessed species that are not classified in a threatened category (e.g. Least Concern [LC], or Near Threatened [NT] in the IUCN Red List), w_{CR}, w_{EN}, w_{VU}, and w_{NotT} are weights applied to the number of CR, EN, VU and not threatened species, respectively, w_j are the weights applied to the number of endangered and threatened species at the national or provincial level. The sum of all $n_{x,y}$ is the total number of species assessed in the basin under the IUCN Red List criteria and/or national or provincial criteria. Weights should be assigned such that $w_{CR} \geq w_{EN} \geq w_{VU} \geq w_{NotT}$ and $w_j \geq w_{j+1} \geq w_{NotT}$.

Invasive and nuisance species (INS_i) also has three components mirroring ISC_i ; and only the first component: the number (i.e. richness) of invasive and nuisance species ($I_{IN,i}$), is calculated based on available data.

$$I_{IN,i} = \begin{cases} 1 - \frac{n_{IN,i}}{10}, & \text{for } 0 \leq n_{IN,i} \leq 8 \\ 0.1, & \text{for } n_{IN,i} \geq 9 \end{cases} \quad (14)$$

where $n_{IN,i}$ is the number of invasive and nuisance species in the basin at time $t = i$.

2. Ecosystem Services Indicator

2.1 Provisioning and Regulating services framework

This category of indicators attempts to measure the impact of Ecosystem services by considering the gap between the supply and demand of services generally associated with freshwater ecosystems. To begin, the basin is divided into spatial units or SUs (generally sub-basins or administrative units) and the supply-demand gap is evaluated over each SU. ‘Failure’ in this case is: inability of supply to meet demand.

The steps of the calculation are:

a) Calculate ‘Scope’

$$\mathrm{F}_1 = \left(\frac{\text{No. of SU failed}}{\text{Total number of SU}}\right) \times 100 \quad (15)$$

b) If data on number of times (instances) failure occurs is available, then calculate ‘Frequency’

$$F_2 = \left(\frac{\text{Number of instances failed}}{\text{Total number of instances}}\right) \times 100 \quad (16)$$

c) If information on scale of failure is available, then calculate ‘Frequency & Magnitude’

For each time step [i] for each SU, excursion beyond threshold for failed instances is calculated as:

$$\mathrm{Ex}_\mathrm{i} = \left(\frac{\text{Failed instance value}_\mathrm{i}}{\text{Threshold}_\mathrm{i}}\right) - 1 \quad (17)$$

Or,

$$\mathrm{Ex}_\mathrm{i} = \left(\frac{\text{Threshold}_\mathrm{i}}{\text{Failed instance value}_\mathrm{i}}\right) - 1 \quad (18)$$

Depending if value must not exceed or fall below the threshold. The values are converted to a scale 0-100 using the following steps:

$$\mathrm{nse} = \frac{\sum_{\mathrm{i=0}}^{\mathrm{n}} \mathrm{Ex}_\mathrm{i}}{\text{Total number of instances}} \quad (19)$$

$$\mathrm{F}_3 = \left(\frac{\mathrm{nse}}{\mathrm{nse+1}}\right) \times 100 \quad (20)$$

d) Based on availability of data, combine values to derive score:

- If able to only determine F1: $ESI = 100 - F1$ (low evidence)
- If able to only determine F1 and F2: $ESI = 100 - \sqrt{F1 \times F2}$ (medium evidence)
- If able to determine all three: $ESI = 100 - \sqrt{F1 \times F3}$ (high evidence)

(21)

2.2 Cultural Services

The two dimensions for cultural services that could be measured are (1) Conservation &

Heritage sites; and (2) Recreation. Selection of context-appropriate methods are highly recommended. For the former, maps of coverage showing protected areas (PAs) can be used. Surveys to measure demand or potential of recreation may be used for the latter. Alternatively, proxies – such as fishing, may be used to estimate recreation value.

3. Governance & Stakeholder survey

The Governance & Stakeholders indicators are based on stakeholders' perceptions and were assessed using a questionnaire consisting of 12 modules corresponding to each sub-indicator, 3-6 questions per module. A total of 49 questions were asked, each using a 1-5 Likert-type scale to quantify the qualitative responses. Responses were consistently phrased so that higher scores on the scale correspond to a more positive assessment. For example, the five questions pertaining to "Water-Related Conflict" use a scale where 1 = Conflicts almost always occur and 5 = Conflicts almost never occur. The questionnaire was administered in English and online (www.typeform.com) through guided exercises at workshops held in each country. The mean value for each response was used to calculate final (sub) indicator scores.

4. Indicator weights using AHP

To ensure that aggregated indicator values for both Ecosystem Services and Governance & Stakeholders reflected stakeholders' preference, stakeholders are surveyed to complete a weighting exercise based on the Analytic Hierarchy Process (Saaty 2005). A hierarchy was created so that stakeholders made a total of 34 pairwise comparisons, first amongst major indicators in each component, and then amongst sub-indicators within a major indicator category. The stakeholders completed the exercise, first by selecting the (sub) indicator they considered more important, and then rating how much more important using a 1-9 intensity scale (where 1 was used to indicate "no preference" between the two objects being compared). These numeric scores were translated into a reciprocal matrix and the principal right eigenvector was calculated to derive weights between 0 and 1. The BPMSG AHP Online System (Goepel 2013) was used to design, administer (in English), and process the exercise. The mean group value was used for weighting aggregated indicators, though individuals' consistency ratios (CR) and the strength of consensus for each choice task are also evaluated.

Supplementary References

Gippel, C. J., Y. Zhang, X. Qu, W. Kong, N. R. Bond, X. Jiang, and W. Liu. 2011. "River Health Assessment in China: Comparison and Development of Indicators of Hydrological Health." Brisbane.

Saffran, Karen, Kevin Cash, and Kim Hallard. 2001. "CCME Water Quality Index 1.0 User's Manual." *Canadian Water Quality Guidelines for the Protection of Aquatic Life*, 1–5. http://www.ccme.ca/files/Resources/calculators/WQI User's Manual (en).pdf.

Table S1. Local and global data sources, models and metrics for evaluating Ecosystem Vitality and Ecosystem Services indicators.

Major indicator	Sub-indicator	Metrics/models	Local and site-scale datasets & models	Global and regional datasets & models
Ecosystem Vitality				
Water Quantity	Deviation from Natural Flow Regime	AAPFD [Gehrke et al., 1995], Hydrologic Deviation [Ladson et al., 1999]	River gauges, hydrological models such as SWAT, HSPF, GSFLOW, etc.	Calibrated instance of Global Hydrologic Models/Land Surface Models such as VIC, WaterGAP, etc.
	Groundwater Storage Depletion	% Area affected	Monitoring wells	GRACE satellite data, land subsidence studies using SAR
Water Quality	Water Quality Index [from TSS, TN, TP and others]	Aggregate of parameter missing WQ targets with frequency and amount with which targets are not met	Local monitoring station, Water quality models such as QUAL, WASP, etc.	NA
Drainage Basin Condition	Bank Modification	Extent of bank/shoreline modified	Aerial Photography	LandSAT imagery, SAR [like Sentinel 1] imagery
	Flow connectivity	Dendritic Connectivity Index [Cote et al., 2009]	Aerial Photography; government database on dams and weir locations	GRanD [Global Reservoir and Dam] Database
	Land cover naturalness	Naturalness Index based on land cover, 0-100 scale	Aerial Photography, Local survey for Land use	MODIS land cover, Global Forest Change database, ESA CCI land cover products
Biodiversity	Change in number and population size of Species of Concern	% Change in number of species and abundance	Local survey	IUCN Red List, national and regional threatened species lists, Global Population Dynamics Database; Global
	Change in number and population size of invasive & nuisance species	% Change in number of species and abundance		

				Invasive Species Database
Ecosystem Services				
Provisioning	Water supply reliability relative to demand	Aggregate of sites affected, frequency and amplitude of gap between water supply and demand	Government regulation records, Water supply and demand models such as WEAP	Water availability information from Global Hydrologic Models/Land Surface Models. Demand estimates based on changes in soil moisture, evapotranspiration, etc. [Nazemi and Wheater, 2015]
	Biomass for consumption	Amount of production or area contributing to biomass, frequency and amplitude of gap between biomass supply and demand	Local monitoring data	NA
Regulation & Support	Sediment Regulation	Aggregate of areas affected, frequency and amount of changes in sediment deposition and erosion thresholds	Reservoir operation and regulation records, hydrological models, Ecosystem service models such as InVEST, ARIES	LandSAT or other high resolution imagery, SAR surveys
	Water Quality Regulation	Aggregate of parameter missing WQ targets with frequency and amount with which targets are not met	Local monitoring stations and authorities	NA
	Flood regulation	Aggregate of sites affected, frequency and amplitude of floods compared to demand	Hydrological models and hydraulic models such as HEC-RAS,etc	NRT Global flood mapping, Global flood risk models [Ward et al, 2015]

	Exposure to water-associated diseases	Aggregate of areas affected, incidence ratio and case-to-fatality ratio	Local monitoring and authorities; WADI modelling approach	Resources such as complied by WHO, Global Infectious Disease and Epidemiology Network [GIDEON], generalized global models from Yang et al [2012]
Cultural	Conservation/Cultural Heritage sites	Area [can be weighted by perceived value]	Government regulation records	World Database on Protected Areas
	Recreation	Person-use days or travel costs	Local survey	Geotagged photographs from social media sites

Table S2. Freshwater Health Index scores and weights for Dongjiang basin

Component	Score	Major indicator	Weight	Score	Sub-indicators	Weight	Score
Ecosystem Vitality	60	Water quantity	0.25	51	Deviation from natural flow	1.0	51
					Change in groundwater supply	--	--
		Water quality	0.25	61	--	--	--
		Basin condition	0.25	56	Bank modification	0.33*	49
					Flow connectivity	0.33*	48
					Land cover naturalness	0.33*	75
		Biodiversity	0.25	73	Index of threatened species	0.50*	76
					Index of invasive species	0.50*	70
Ecosystem Services	82	Provisioning	0.61	86	Water supply reliability	0.83	86
					Biomass for consumption	0.17	--
		Regulating	0.28	73	Sediment regulation	0.09	75
					Water quality regulation	0.31	72
					Flood regulation	0.33	73
					Disease regulation	0.27	--
		Cultural	0.11	--	Conservation & cultural heritage	0.65	--
					Recreation	0.35	--
Governance & Stakeholders	56	Enabling Environment	0.28	54	Water resource management	0.31	57
					Rights to resource use	0.14	57
					Incentives & regulations	0.22	47
					Financial capacity	0.21	--
					Technical capacity	0.13	59
		Stakeholder Engagement	0.17	47	Information access	0.54	50
					Engagement in decision-making	0.46	44
		Vision & Adaptive Governance	0.22	59	Strategic planning	0.70	58
					Monitoring mechanisms	0.30	60
		Effectiveness	0.34	54	Enforcement and compliance	0.46	60
					Distribution of benefits	0.21	50
					Conflict	0.33	48

*These are default weights, not adjusted by stakeholders