

# 1 **Integrating the social, hydrological and ecological dimensions of**

## 2 **freshwater health: the Freshwater Health Index**

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37

38 **Abstract**

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

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

60

## 61 **1. Introduction**

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

75           There are a variety of existing methods and indicators for characterizing these multi-  
76 faceted challenges, though they are typically biased toward a disciplinary (e.g., hydrology,  
77 ecology, or economics) framing of the problem (Vogel et al., 2015). Pires et al. (2017) evaluated  
78 water-related indicators against social, economic, environmental and institutional criteria and  
79 find that integrative, multi-metric indices are best-suited to measuring the complexity of water  
80 resource sustainability. Vollmer et al. (2016) reviewed 95 distinct indices (and indicator  
81 frameworks) and found that although a subset of these multi-metric indices included biological,  
82 physical, and social indicators, they typically did not consider interactions among these  
83 dimensions, such as the link between ecological function and ecosystem services. For example,

84 the role that freshwater ecosystems play in providing and regulating water storage and flows for  
85 human use is frequently overlooked in water resource management (Baron et al., 2002; Green et  
86 al., 2015).

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

98         To meet the challenges of ensuring freshwater security, a conceptualization of freshwater  
99 resources as social-ecological systems is required, along with a set of indicators to measure  
100 freshwater health and highlight areas for management. “Freshwater health” is defined here as the  
101 ability of freshwater ecosystems to deliver ecosystem services and benefits, sustainably and  
102 equitably, through effective management and governance. This definition of health is a departure  
103 from existing comparable terms such as “river health” (e.g., Boulton, 1999; Karr, 1999; Dos  
104 Santos et al., 2011) or “ecosystem health” (e.g., Xu et al., 1999; O’Brien et al., 2016), which use  
105 ecological endpoints as proxies for an ability to meet human demands. By defining health as an  
106 ability to actually deliver services, and recognizing the role of governance in this, we adhere

107 closer to definitions presented by Meyer (1997) for “stream health” and Vugteveen et al.’s  
108 (2006) definition of “river system health”, both of which propose including information on  
109 human attitudes and social institutions. We thus define sustainable water use as the long-term use  
110 of water in sufficient quantity and with acceptable quality to support human well-being and  
111 socio-economic development, to ensure protection from water-associated disasters, pollution and  
112 disease, and to preserve ecosystems.

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

123

## 124 **2. Conceptualizing freshwater resources as social-ecological systems**

### 125 2.1 Conceptual framework for freshwater social-ecological systems (SES)

126 The freshwater social-ecological conceptual framework was developed through an extensive  
127 literature review (Vollmer et al., 2016), two interdisciplinary scientific workshops held in  
128 December 2015 and July 2016, and consultations with stakeholders from the Pearl River and  
129 Mekong River basins in July and November 2016. It builds on Ostrom’s (2009) general social-

130 ecological systems framework by characterizing freshwater systems as dynamic social-  
131 ecological networks, with linkages and feedbacks that highlight human water uses, the effects of  
132 these uses on freshwater ecosystems and, importantly, the role that governance plays in the  
133 sustainable and equitable delivery of water-based services through the maintenance of  
134 functioning ecosystems (Fig. 1). It illustrates the different dimensions that need to be measured  
135 in order to understand how social, hydrologic and ecological systems interact. Watersheds  
136 provide a logical physical boundary for conceptualizing a freshwater SES, given that water  
137 moves through watersheds from higher to lower elevations and watersheds also include  
138 underground water movement and storage. Depending on data availability, the framework  
139 described here is scalable and can be applied to sub-basins or multiple adjoining basins (to  
140 account for inter-basin transfers) on up to national-level assessments and international  
141 transboundary basins.

142         Our conceptual framework for freshwater SESs consists of: Ecosystem Vitality,  
143 Ecosystem Services, Governance and Stakeholders (Fig. 1). Governance here refers to the  
144 “structures and processes by which people in societies make decisions and share power, creating  
145 the conditions for ordered rule and collective action, or institutions of social coordination”  
146 (Schultz et al. 2015, pg. 7369). This definition encompasses multiple tiers of governments, their  
147 formal rules and informal norms (e.g., community-established guidelines), non-governmental  
148 processes for collective action and decision-making and market mechanisms. Stakeholders are  
149 actors who depend on freshwater services from a basin or are involved in the decisions that affect  
150 these services. This includes individual citizens, community groups, municipalities, and  
151 corporations that have a *de facto* right to the benefits of water. Other stakeholders include entities  
152 such as non-governmental and international organizations that may not directly benefit from the

153 ecosystem services in a particular location, but nonetheless have an interest in, and influence  
154 over, decisions that affect the basin. Stakeholders operate within the constraints of a governance  
155 system that affects their behavior but, in turn, stakeholders also may influence or shape the  
156 governance system by modifying rules or changing the composition of the system.

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

171

## 172 2.2 Identifying Indicators of Freshwater Health

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



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

183

### 184 2.2.1 Indicators for Ecosystem Vitality

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

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

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

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

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

212

### 213 2.2.2 Indicators for Ecosystem Services

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

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

222 production such as fisheries, fiber and wild food.

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

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

232

### 233 2.2.3 Indicators for Governance & Stakeholders

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

241 *Enabling environment* reflects the constraints and opportunities that are enshrined by  
242 policies, regulations, market mechanisms and social norms in governing and managing  
243 freshwater resources. It includes the extent to which typical water resource management  
244 functions (monitoring and coordination, planning and financing, developing and managing

245 infrastructure, and resolving conflicts) are implemented through policies, institutions,  
246 management tools, financing and accounting for various users and uses. It also considers the  
247 coherence of existing rights to resource use, including how water, land and fishing rights are  
248 allocated, customary rights (including land tenure), and the degree to which these work in  
249 conjunction with formalized rights. Availability of different management instruments, as well as  
250 the capacity of skilled professionals working in water resource management fields, is also  
251 captured here.

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

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

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

263

### 264 **3. Methods**

#### 265 3.1 Measurement and Aggregation of the Indicators

266 Sub-indicator values for Ecosystem Vitality and Ecosystem Services are generally based  
267 on spatially distributed, monitored or modeled data across sub-basins or administrative

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

280         Once sub-indicator values at the basin-scale were estimated, they were normalized to a  
281 common non-dimensional scale of 0-100, where higher values denoted a positive assessment of  
282 that dimension in regard to sustainable freshwater health. Sub-indicators with a negative  
283 connotation, such as “Bank modification” and “Water-Related Conflict”, thus use an inverted  
284 scale. These non-dimensional sub-indicator values were then aggregated via a geometric mean to  
285 provide an overall value for each major indicator. The major indicators were further aggregated  
286 (again using the geometric mean) to provide an index value for each component. The indices  
287 were not further aggregated across the three components since demonstrating the values for the  
288 three main components separately can highlight the source of the greatest problems or the most  
289 prominent factors contributing to sustainability. High index values across all three components  
290 are indicative of a sustainable freshwater ecosystem. A low value for a component, a major

291 indicator or a sub-indicator highlights an area for improvement. For instance, a low value for the  
292 Ecosystem Vitality index can serve as an early warning signal that ecosystems cannot  
293 sustainably provide water-based ecosystem services or maintain biodiversity; a low value for the  
294 Ecosystems Services index signals that societal water needs are not being met; or a low value for  
295 the Governance & Stakeholders index can elucidate processes that stakeholders can change in  
296 order to realize improvements in Ecosystem Vitality and Ecosystem Services.

297         Prior to aggregation, weights can be applied to denote greater or lesser importance of the  
298 role of each indicator for assessing freshwater health in the basin. As we demonstrate with the  
299 application in the Dongjiang basin, this weighting exercise provides not only a quantitative input  
300 to the aggregation of sub-indicators, but also reveals stakeholders' preferences. There are a  
301 variety of methods for assigning weights including, but not limited to, expert elicitation (Morgan,  
302 2014), the Delphi method (Linstone & Turoff, 1975), or the Analytic Hierarchy Process (AHP)  
303 (Saaty, 2005). We apply the AHP method as it is well-suited to our hierarchical indicators and  
304 allows a large number of stakeholders to provide input, recognizing that the relative importance  
305 of Ecosystem Services and Governance & Stakeholders indicators is a subjective matter.

306

### 307 3.2 Application in the Dongjiang River Basin

308         We illustrate the application of the Freshwater Health Index through a case study of the  
309 Dongjiang basin, which is the eastern tributary of the Pearl River)—Zhujiang)—in southern  
310 China (Fig. 2). The case study served two main objectives. First, it subjected our framework to  
311 the real-world challenge of providing decision-relevant insights, by working directly with  
312 stakeholder groups in the basin. Second, it tested the ability of our framework to assimilate  
313 suitable metrics based on available local and global datasets. With an annual average discharge

314 of 739 m<sup>3</sup>/s and basin area of 35,340 km<sup>2</sup>, the Dongjiang is the smallest tributary of the three  
315 main rivers comprising the Pearl River system. Despite its size, the Dongjiang is the primary  
316 water source for more than 40 million residents, including the world's largest urban  
317 agglomeration. Beginning in the late 1950s, dams were constructed to provide flood control and  
318 hydropower but, as the delta population grew and urbanized, water allocation and quality have  
319 emerged as top priorities. Socioeconomically, there is a substantial disparity between the rural  
320 upstream communities and the urban areas (including Shenzhen and Hong Kong) in the delta—  
321 per capita GDP is at least 10 times greater downstream. This provides an impetus to maximize  
322 the productive use of land upstream through mining, intensified agriculture and industrial  
323 relocation, which could bring short-term economic development but threaten water-related  
324 ecosystem services.

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

335         For the Dongjiang basin, quantitative information to evaluate the indicators primarily  
336 came from in situ monitored water quality and discharge data sets, provincial statistical

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

352

## 353 **4. Results & Discussion**

### 354 4.1 Weights and Indicator Scores for Dongjiang Basin

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



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

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

377

#### 378 4.2 Interpretation of Scores for the Basin

379         Results for the Dongjiang basin generally met our expectations, but also highlighted  
380 issues for further analysis or data collection. The summary scores suggest that human needs are  
381 currently being met fairly well (Ecosystem Services score of 82) but at the expense of the  
382 region's ecology (Ecosystem Vitality—60), and the current governance structure may need to be

383 reformed (score of 56) to address this imbalance and handle future challenges like population  
384 growth and climate change. While it may appear counterintuitive to have high Ecosystem  
385 Service scores but lower scores for other components, we posit two interpretations. The first is  
386 that there are often tradeoffs between maintaining elements of Ecosystem Vitality and  
387 maximizing certain services such as water provision or flood regulation, thus some negative  
388 correlation is expected. For example, given the high degree of regulation of surface water in the  
389 basin, the low score for Water Quantity under Ecosystem Vitality, which measures shifts in the  
390 seasonal flow pattern, is not surprising (nor are the low scores for Bank Modification and Flow  
391 Connectivity). Second, there is likely a time lag and thresholds before we might observe positive  
392 correlations among sub-indicators—this can be explored through more historical analysis but  
393 requires further research and long-term monitoring of the governance sub-indicators.

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

404         Water Quality received the highest weight among Regulation and Support services  
405 (which include flood, sediment and water-associated disease regulation), reflecting stakeholders’

406 concerns with deteriorating water quality in the basin. This is something that has received  
407 significant attention from local governments (Lee and Moss, 2014) with the establishment of  
408 additional monitoring stations and the introduction of ‘polluter pays’ systems. And while the  
409 Water Quality indicator suggested moderate health for human consumption purposes (72), fecal  
410 coliform levels were regularly higher than the threshold (China’s Class II standard of 2000/L) at  
411 all four monitoring stations as a result of unregulated discharges of municipal waste. With the  
412 growing industrialization of the mid-stream sections and the downstream decline in freshwater  
413 biodiversity that is evident already (Zhang et al 2010), water quality monitoring requires further  
414 attention.

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

429 with previous assessments of ecological health for the basin (Wang et al., 2011; Jiang et al.,  
430 2015), which note channelization, fragmentation and flow modification as being areas of greatest  
431 concern in an otherwise ecologically healthy basin.

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

446 Finally, the indicator scores for Flood Regulation and Sediment Regulation highlight the  
447 changing character of this river system and the trade-offs associated with river infrastructure  
448 development. While floods were historically a frequent natural disaster in the basin (Liu et al.  
449 2012), channelization of the downstream segments and reservoir storage have greatly reduced  
450 floods as a major threat. However, these modifications have impacted the sediment dynamics of  
451 the system. The Basin Condition score (62) reflects this modification, but suggests that the basin

452 has only seen moderate impacts of the modification of its stream network. The bank modification  
453 is concentrated at the downstream end of the river basin; however, the main reservoirs also exert  
454 a strong influence on sedimentation; sediment flow at the outlet has more than halved between  
455 1955 and 2005 based on observed records (Dai et al. 2008), which affects the amount of nutrients  
456 reaching the estuary as well as brackish water intrusion upstream. Furthermore, increases in  
457 urbanization in the region over recent years has led to increased riverbed dredging to meet  
458 demand for gravel and related construction material. This has been associated with a fall in river  
459 bed level, measured at a downstream gauge (Boluo), by 1-1.5 m between 1995-2002 (Liu et al.,  
460 2012) and an expected weakening of the flood levees. Despite these changes and potential risks,  
461 empirical data on sediment loss were not easily accessible, and we relied on modeled data to  
462 estimate sediment regulation. It is essential to set up a system for regular monitoring of dredging  
463 and its consequences for levee stability.

464

#### 465 4.3 Stakeholder Engagement under the Framework

466 This initial application of the Freshwater Health Index revealed useful information about  
467 the Dongjiang basin, but also about the framework and its generalizability. It represented the first  
468 comprehensive assessment of the Dongjiang River basin within a social-ecological framework—  
469 previous assessments focused on either water quantity or water quality issues separately, and did  
470 not address issues such as biodiversity, land use, ecosystem services, or governance. In this  
471 regard, the Freshwater Health Index provided a framework for evaluating these various  
472 dimensions concurrently and, more importantly, a framework upon which to base discussions of  
473 the relationships and interactions among these variables within the Dongjiang basin. The concept  
474 of ecosystem services was new to many workshop participants, but it could be succinctly

475 illustrated by reference to the protected areas that surround the basin’s three main reservoirs—  
476 these mountainous areas maintain mostly forested land cover in order to safeguard water  
477 supplies, but at the same time provide recreational amenities within a 2-hour drive of the  
478 populous urban centers of the Pearl River Delta.

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

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

515

#### 516 4.4 Extensions of the Freshwater Health Index

517           The Freshwater Health Index is intended primarily for within-basin comparisons over  
518 time, or via scenarios, rather than across basins, to allow for basin-specific flexibility in terms of  
519 data inputs and measurement methods. Within a basin, historical data analysis and scenario  
520 modeling can help establish the sensitivity of indicator values. Such sensitivity analyses are

521 identified as a next step to gauge whether improvements to freshwater sustainability are  
522 occurring as rapidly as expected in response to management actions, or whether a modest decline  
523 should be of major concern requiring prompt action. It is in the examination and response to  
524 these relative shifts that the index values have the greatest utility, rather than the absolute  
525 component values of the Freshwater Health Index. More research will be needed to understand  
526 how, and under what circumstances, changes in sub-indicators are linked. A single snapshot of  
527 the FHI cannot reveal these linkages, but additional historical analysis (where data are sufficient)  
528 and quantitative modeling should both help identify issues such as time lags, thresholds, and  
529 sensitivity to changes. This, in turn, would help users understand links between ecosystem health  
530 and service delivery, and to identify tradeoffs before they occur.

531         The FHI indicators and suggested metrics are designed to make use of existing data, but  
532 since data availability varies considerably around the world, it is also useful in highlighting data  
533 gaps and thus setting priorities for data collection or organization. This highlights the importance  
534 of having a conceptual framework guiding indicator selection, as opposed to biasing an index  
535 toward existing data or unsuitable proxies—a full understanding of freshwater health will likely  
536 require additional efforts in data collection. Cultural services were the most notable gap for the  
537 Dongjiang basin, though this was not unexpected as cultural ecosystem services are less  
538 commonly evaluated than material services, and more difficult to create proxies from routinely  
539 collected data (Chan et al., 2012). Given the relatively high weight stakeholders placed on  
540 Conservation and Cultural Heritage, despite not having existing data on its condition, work is  
541 now underway to develop a locally-relevant metric that can be re-evaluated over time.  
542 Stakeholders also expressed interest in providing more local data to improve the spatial  
543 resolution of disaggregated sub-indicator evaluations and ensure that data were all covering the



544 same time period. Without a unifying framework such as the Freshwater Health Index there was  
545 little incentive to share these data throughout the basin.

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

561         Stakeholders in the Dongjiang River basin expressed a strong interest in exploring future  
562 changes via scenarios. These scenarios include future economic development—increased  
563 urbanization and industrial relocation to upstream areas of Huizhou and Heyuan—as well as  
564 climate change, which may create more frequent extreme events (floods and droughts) in the  
565 basin (Yang et al., 2016). Thus, a next step in the basin would be to develop detailed scenarios  
566 with stakeholders and then model these scenarios with a suite of hydrologic, quality, hydraulic,

567 soil loss, and allocation models to evaluate changes in specific Ecosystem Vitality and  
568 Ecosystem Services indicators relative to this initial baseline assessment. Not all indicators can  
569 be quantitatively modeled using this approach, but for those that can, this step will also help  
570 stakeholders identify undesirable trade-offs and possible synergies, and begin setting targets for  
571 the basin's health. And by repeating the assessment over time (e.g., 3-5 years), the Index allows  
572 users to test hypotheses about how improved water governance leads to better outcomes as  
573 measured in Ecosystem Services and Ecosystem Vitality. Using this common framework across  
574 a variety of basins, it is even possible to develop a knowledge base over time on the empirical  
575 relationship between changes in governance, ecosystems and benefits.

576

577

## 578 **5. Conclusion**

579 The social-ecological framework presented here, and the indicators derived from it, take  
580 account of the interplay between governance, stakeholders, freshwater ecosystems and the  
581 ecosystem services they provide. This reflects the fact that each of these components must be  
582 assessed, monitored and managed, with equal consideration, to achieve a realistic and pragmatic  
583 understanding of freshwater sustainability and the way it can be achieved. The Freshwater Health  
584 Index framework and its accompanying indicators are oriented toward management and  
585 stakeholder engagement, and they make a significant contribution by providing a systematic,  
586 evidence-based quantitative tool that supports the integrative social and ecological nature of  
587 fresh waters at the basin level. The Freshwater Health Index is flexible in that it can be adapted  
588 to a wide range of contexts and user needs, providing a much needed implementation tool for

589 operationalizing IWRM. This paper has shown one such demonstration in the Dongjiang basin,  
590 where local anthropogenic pressures are high and integrated management is currently weak.

591         The Index is intended to be used iteratively, testing scenarios and informing data  
592 collection and monitoring over time. With the aid of hydrologic and ecosystem service models,  
593 this can be used to analyze proposed management plans or uncertain future scenarios, thereby  
594 assisting in decision-making and policy development. By explicitly juxtaposing the social and  
595 ecological dimensions of the problem within a consistent framework, the human need for water  
596 is linked with the ability of freshwater ecosystems to meet those needs without compromising  
597 habitat integrity or threatening biodiversity. The Index also highlights the vital, yet much  
598 neglected, role of governance in safeguarding the delivery of these services in an equitable and  
599 sustainable manner. Moreover, this framework is explicitly designed to support concerted  
600 international efforts such as the UN Sustainable Development Goals (SDGs) (United Nations  
601 2015) and the International Panel on Biodiversity and Ecosystem Services (Diaz et al 2015),  
602 which recognize the interlinked social and ecological dimensions of sustainable ecosystem  
603 service provision.

604

605

## 606 **Acknowledgments**

607 This work was funded by grants from the Victor and William Fung Foundation, Betty and  
608 Gordon Moore, the Borrego Foundation and the Australian Research Council [LP130100498].

609

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920

921 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 <sup>1</sup> Total nitrogen in surface and groundwater <sup>1</sup> Total phosphorous in surface and groundwater <sup>1</sup> Indicators of major concern <sup>2</sup>
Drainage-basin condition	Percent of channel modification (bank modification) Dendritic connectivity index (flow connectivity) Land cover naturalness <sup>3</sup>
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

- 922 1. Deviation of concentration from environmental benchmark related to local historic  
923 natural conditions.
- 924 2. Optional; depends on local conditions and could include salinity, dissolved oxygen, pH,  
925 electrical conductivity, total dissolved solids, heavy metals and coliforms, as well as  
926 pharmaceuticals and other contaminants.
- 927 3. Naturalness here is measured on a gradient from completely natural (e.g., primary forest)  
928 to completely artificial (e.g., urban areas).
- 929

930

931 Table 2. Ecosystem Services indicators

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

932 1. Optional; include depending on local conditions

933 2. Refers to ability of the freshwater ecosystem to deliver water of the expected water-quality  
934 standards for different sectors.

935

936

937 Table 3. Governance & Stakeholders indicators

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

938

939

940

941

942  
943 Figure 1. Conceptual framework for freshwater SESs comprised of Governance and  
944 Stakeholders, Ecosystem Vitality and Ecosystem Services. Stakeholders set and adapt rules  
945 within governance and market systems and also respond to them. Within the constraints and  
946 rules set by water governance, stakeholders modify ecosystems through land-use change or  
947 conservation in order to exploit or manage freshwater ecosystems, and also by developing  
948 infrastructure and technology to access water-based ecosystem services. Modifications to  
949 ecosystems and water withdrawals can alter the flow regime and water quality and thereby affect  
950 delivery of ecosystem services to beneficiaries. In basins where there are competing water needs,  
951 tradeoffs become apparent and may necessitate an adjustment to governance mechanisms that  
952 can trigger changes in markets. Freshwater SESs are also impacted by external biophysical  
953 influences such as drought or climate change that affect ecosystem service delivery that can feed  
954 back to affect governance. Basins are also embedded within a broader social, political and  
955 economic context that can influence governance systems and thus management of fresh waters.  
956 While we recognize that water and water-based goods and services may also be imported into or  
957 exported from a basin, our focus is primarily on interactions within the basin.

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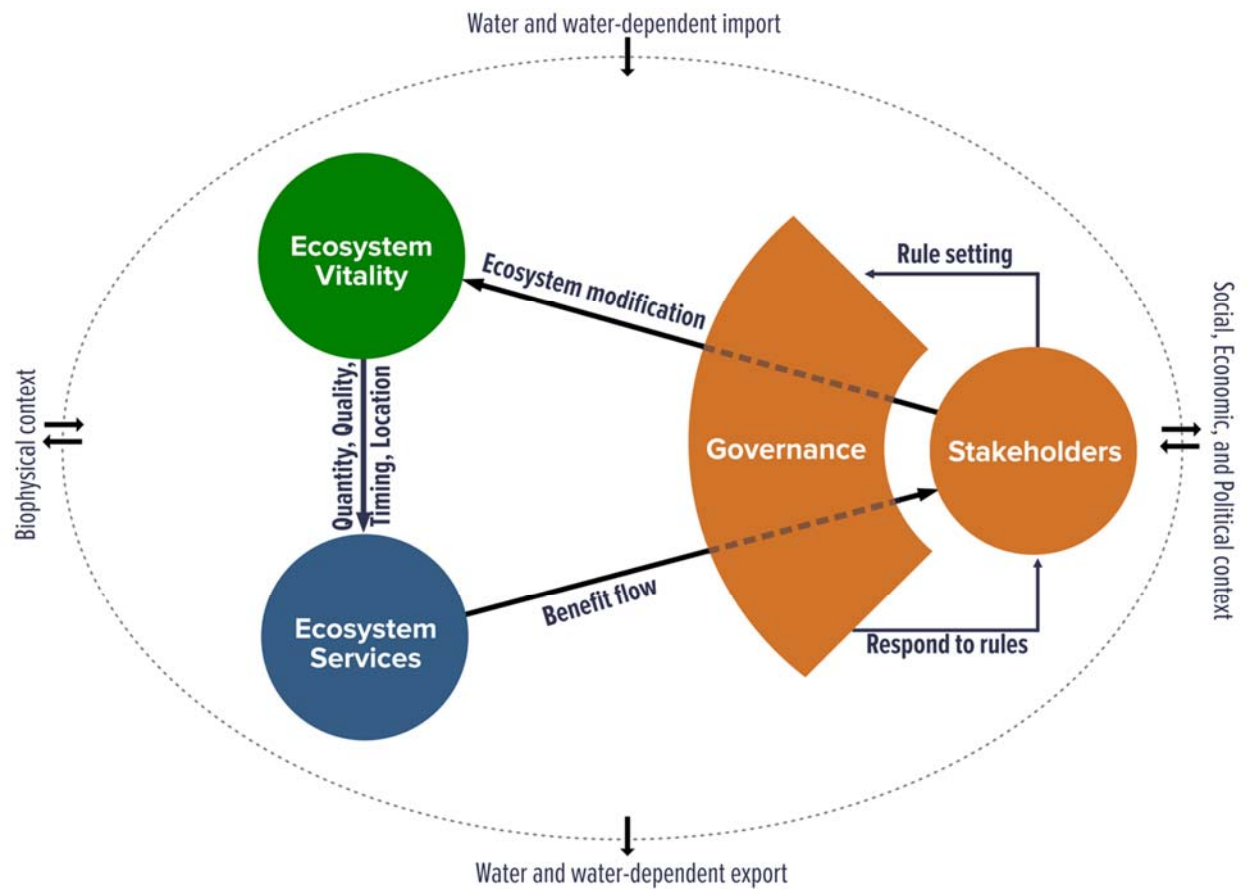
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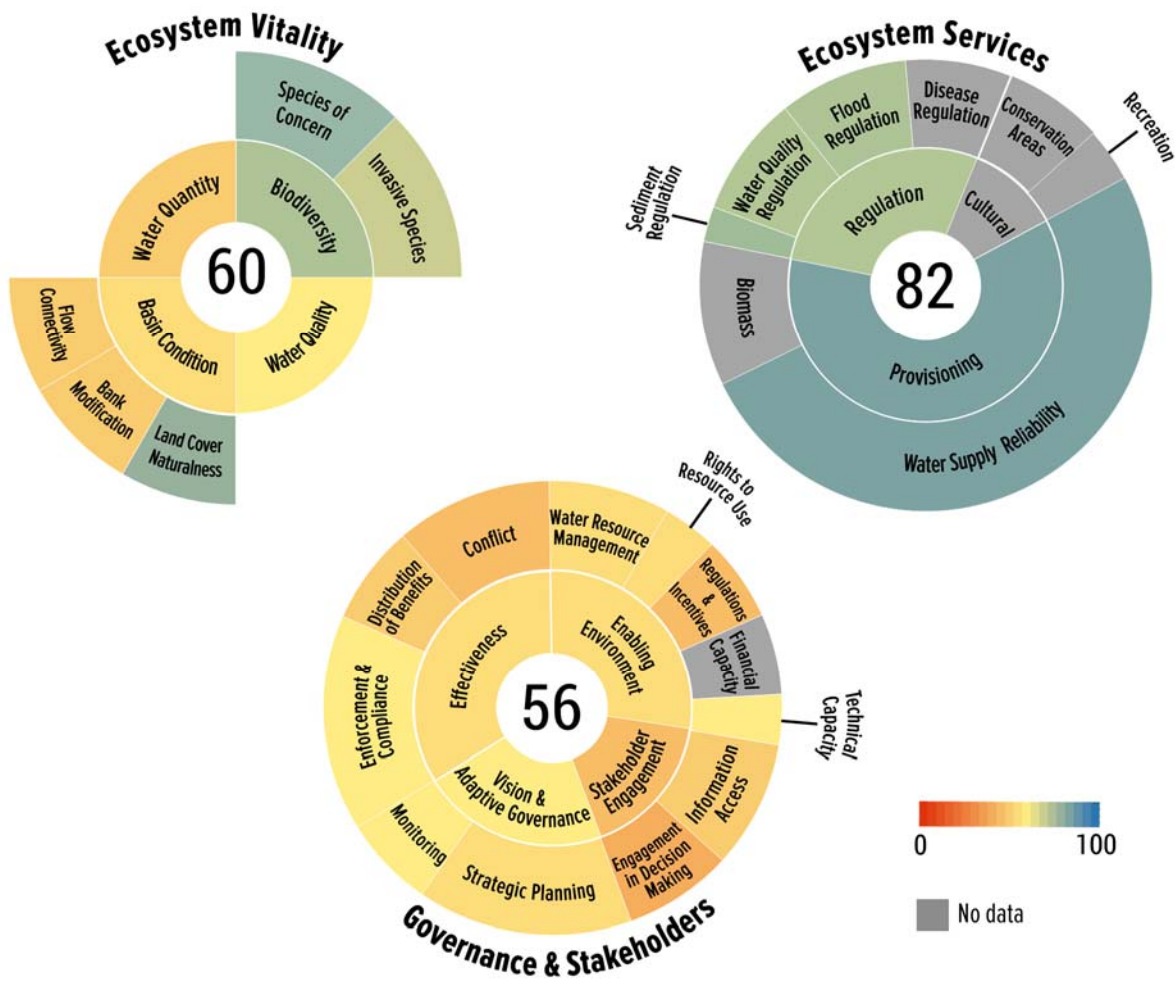
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966 Figure 2. Dongjiang basin (shaded) in southern China. Major municipalities are highlighted in  
967 bold text and demarcated with dashed lines. Reservoirs are labeled in italics.



968

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

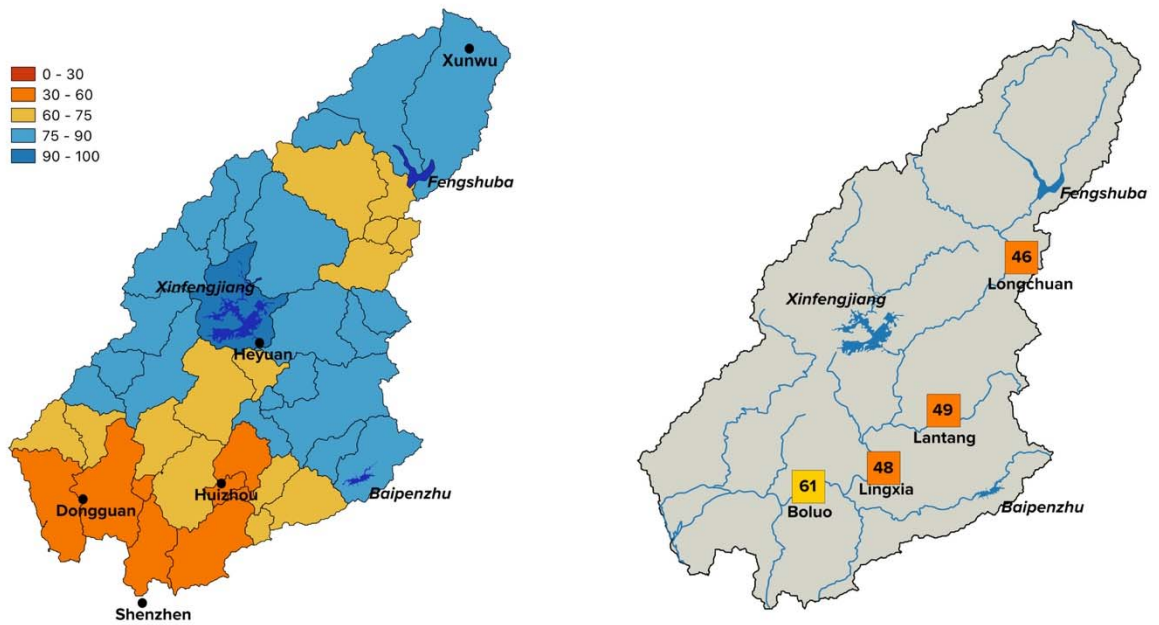


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974 Figure 4. Spatial disaggregation of scores for Land Cover Naturalness (left, at sub-basin scale)  
975 and Deviation from Natural Flow (right, from monitoring stations). Mapping these indicators  
976 helps reveal variability within the basin,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



980

1

2

## 1 Text S1. Freshwater Health Index: Methods

2 The sections below provide an overview of the  
3 calculation process for indicators used in the  
4 manuscript and is derived from the 'Freshwater  
5 Health Index user manual v1.1'. The authors  
6 encourage readers interested in detailed  
7 description of the methods as well as explanation  
8 of data sources and sample questionnaires to refer  
9 to the user manual (available at:  
10 [www.freshwaterhealthindex.org](http://www.freshwaterhealthindex.org))

11 All indicators are scaled in range 0-100.

### 12 1. Ecosystem Vitality Indicators

#### 13 1.1 Water Quantity

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

$$21 \text{ AAPFD} = \sum_{j=1}^p \frac{\sqrt{\sum_{i=1}^{12} \left[ \frac{m_i - n_i}{\bar{n}_i} \right]^2}}{p} \quad (1)$$

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

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

$$31 \text{ DvNF} = \begin{cases} 100 - 100 \times \text{AAPFD} & \text{for } 0 \leq \text{AAPFD} < 0.3 \\ 85 - 50 \times \text{AAPFD} & \text{for } 0.3 \leq \text{AAPFD} < 0.5 \\ 80 - 20 \times \text{AAPFD} & \text{for } 0.5 \leq \text{AAPFD} < 2 \\ 50 - 10 \times \text{AAPFD} & \text{for } 2 \leq \text{AAPFD} < 5 \\ 0 & \text{for } \text{AAPFD} \geq 5 \end{cases} \quad (2)$$

33

#### 34 1.2 Water Quality

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

46 a) Calculate 'Scope'

$$47 F_1 = \left( \frac{\text{Number of failed parameters}}{\text{Total number of parameters}} \right) \times 100 \quad (3)$$

49 b) Calculate 'Frequency & Magnitude'

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

$$53 \text{ Ex}_i = \left( \frac{\text{Failed test value}_i}{\text{Threshold}_i} \right) - 1 \quad (4)$$

54 Or,

$$55 \text{ Ex}_i = \left( \frac{\text{Threshold}_i}{\text{Failed test value}_i} \right) - 1 \quad (5)$$

56 Depending if value must not exceed or fall below  
57 the threshold. The values are converted to a scale  
58 0-100 using the following steps:

$$59 \text{ nse} = \frac{\sum_{i=0}^p \text{Ex}_i}{\text{Total number of tests}} \quad (6)$$

$$60 F_3 = \left( \frac{\text{nse}}{\text{nse}+1} \right) \times 100 \quad (7)$$

61 c) The F1 and F3 are combined:

$$62 \text{ WQI} = 100 - \sqrt{F_1 \times F_3} \quad (8)$$

#### 63 1.3 Drainage basin condition

64 The sub-indicators under this attempt to account  
65 for state of the surface waterbodies as well as

1 landcover on freshwater health. Some of the  
2 indicators considered are:

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

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

$$10 \quad DCI_p = \sum_{i=1}^n \frac{l_i^2}{L^2} \quad (9)$$

$$11 \quad DCI_d = \frac{l_0}{L} \quad (10)$$

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

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

18 For each sub-basin, based on location of levees,  
19 dykes, channelization, clearance of instream  
20 obstructions to navigation, reservoir extent etc.,  
21 the percentage length affected can be calculated  
22 (0 for near-natural, 1 for fully channelized).  
23 Scores for [i] sub-basins are combined using:

$$24 \quad pCM = \left(1 - \frac{\sum_{i=1}^n l_i pCM_i}{L}\right) * 100 \quad (11)$$

25 where,  $L$  is the river network length,  $l_i$  is the  
26 length of the river fragment in  $i^{th}$  sub-basin.

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

29 A Degree of Naturalness classification matrix is  
30 applied to each land-cover/land use (LULC)  
31 category available from the LULC map of the  
32 basin. The proposed weighting for “naturalness”  
33 in the matrix should include ranges of values to  
34 help highlight transitions from “natural” to  
35 “transformed” systems, i.e., from forests and  
36 wetlands to cultivated lands or from cultivated

37 lands to urban areas – and is prepared/refined  
38 with help of local expert opinion.

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

#### 42 1.4 Biodiversity

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

46 Species of concern ( $ISC_i$ ) has three components  
47 (1) the proportion of threatened freshwater  
48 species ( $I_{TE,i}$ ), (2) change in the number of  
49 species of concern ( $\Delta SC_i$ ), and (3) average  
50 population trend across all species of concern  
51 ( $PT_i$ ). These three parameters are then combined  
52 to give an overall index for the status and change  
53 in species of concern.

$$54 \quad ISC_i = \min\{ISC_{i-1} \sqrt[3]{I_{TE,i} \times \Delta SC_i \times PT_i}, 100\} \quad (12)$$

55 Due to data availability constraints, only  $I_{TE,i}$  is  
56 calculated and  $\Delta SC_i$  or  $PT_i$  were set to equal 1 for  
57 the calculation of  $ISC_i$ .  
58

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

$$67 \quad I_{TE,i} = 1 - \frac{w_{CR}n_{CR,i} + w_{EN}n_{EN,i} + w_{VU}n_{VU,i} + \sum_j w_j n_{j,i}}{(w_{CR}n_{CR,i} + w_{EN}n_{EN,i} + w_{VU}n_{VU,i} + \sum_j w_j n_{j,i} + w_{NotT}n_{NotT})} \quad (13)$$

68 where  $n_{CR,i}$ ,  $n_{EN,i}$ , and  $n_{VU,i}$  are the number of  
69 species listed as CR, EN, or VU under the IUCN  
70 Red List categories and criteria at time  $t = i$ ,  
71 respectively,  $n_{j,i}$  is the number of species  
72 classified in an endangered or threatened  
73 category at the national or provincial level at time  
74  
75

1  $i$  (e.g., for regions that classify species as  
2 “endangered” or “threatened”,  $j=1$  refers to the  
3 endangered category and  $j=2$  refers to the  
4 threatened category),  $n_{NotT}$  refers to the  
5 remaining assessed species that are not classified  
6 in a threatened category (e.g. Least Concern  
7 [LC], or Near Threatened [NT] in the IUCN Red  
8 List),  $w_{CR}$ ,  $w_{EN}$ ,  $w_{VU}$ , and  $w_{NotT}$  are weights  
9 applied to the number of CR, EN, VU and not  
10 threatened species, respectively,  $w_j$  are the  
11 weights applied to the number of endangered and  
12 threatened species at the national or provincial  
13 level. The sum of all  $n_{x,y}$  is the total number of  
14 species assessed in the basin under the IUCN Red  
15 List criteria and/or national or provincial criteria.  
16 Weights should be assigned such that  $w_{CR} \geq$   
17  $w_{EN} \geq w_{VU} \geq w_{NotT}$  and  $w_j \geq w_{j+1} \geq w_{NotT}$ .

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

$$23 \quad I_{IN,i} = \begin{cases} 1 - \frac{n_{IN,i}}{10}, & \text{for } 0 \leq n_{IN,i} \leq 8 \\ 0.1, & \text{for } n_{IN,i} \geq 9 \end{cases} \quad (14)$$

24  
25  
26 where  $n_{IN,i}$  is the number of invasive and  
27 nuisance species in the basin at time  $t = i$ .  
28

## 29 2. Ecosystem Services Indicator

### 30 2.1 Provisioning and Regulating services 31 framework

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

41 The steps of the calculation are:

42 a) Calculate ‘Scope’

$$43 \quad F_1 = \left( \frac{\text{No. of SU failed}}{\text{Total number of SU}} \right) \times 100 \quad (15)$$

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

$$46 \quad F_2 = \left( \frac{\text{Number of instances failed}}{\text{Total number of instances}} \right) \times 100 \quad (16)$$

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

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

$$52 \quad Ex_i = \left( \frac{\text{Failed instance value}_i}{\text{Threshold}_i} \right) - 1 \quad (17)$$

53 Or,

$$54 \quad Ex_i = \left( \frac{\text{Threshold}_i}{\text{Failed instance value}_i} \right) - 1 \quad (18)$$

55 Depending if value must not exceed or fall below  
56 the threshold. The values are converted to a scale  
57 0-100 using the following steps:

$$58 \quad nse = \frac{\sum_{i=0}^n Ex_i}{\text{Total number of instances}} \quad (19)$$

$$59 \quad F_3 = \left( \frac{nse}{nse+1} \right) \times 100 \quad (20)$$

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

- 62 • If able to only determine F1:  $ESI = 100 - F_1$  (low evidence)
- 63
- 64 • If able to only determine F1 and F2:  $ESI =$   
65  $100 - \sqrt{F_1 \times F_2}$  (medium evidence)
- 66 • If able to determine all three:  $ESI = 100 -$   
67  $\sqrt{F_1 \times F_3}$  (high evidence)

$$68 \quad (21)$$

### 69 2.2 Cultural Services

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

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

### 9 3. Governance & Stakeholder survey

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

55

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63

### 28 4. Indicator weights using AHP

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

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

3

Major indicator	Sub-indicator	Metrics/models	Local and site-scale datasets & models	Global and regional datasets & models
<b>Ecosystem Vitality</b>				
<i>Water Quantity</i>	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
<i>Water Quality</i>	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
<i>Drainage Basin Condition</i>	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
<i>Biodiversity</i>	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		

Ecosystem Services				
<i>Provisioning</i>	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 Wheeler, 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
<i>Regulation &amp; Support</i>	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 compiled by WHO, Global Infectious Disease and Epidemiology Network [GIDEON], generalized global models from Yang et al [2012]
<i>Cultural</i>	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

1

2

1 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							

2