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A Nation-Wide Framework for Evaluating Freshwater Health in China: Background, Administration, and Indicators

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Abstract: This study reviewed the existing experience of implementing the nation-wide freshwater health evaluation in China and around the world and proposes a new framework that works in collaboration with the River Chief System (RCS). The institutional context of China with intertwined political and scientific considerations makes it essential to establish a concise and quantitative approach to assess the effectiveness of the RCS as well as local freshwater health conditions that can be easily understood by non-experts for decision-making. To fulfil this objective, we reconstructed the indicator categories based on the best practices in major western countries and the existing regional standards in China. The new indicator framework includes two main aspects: Ecosystem integrity (physical habitat, water quantity, water quality, and aquatic life) and non-ecological performance (social services and water governance). Specifically, the non-ecological attributes of freshwaters are in accordance with the purposes of the RCS and are usually ignored in many countries. The final health grade for a specific water body is determined by a weighted averaging method; this grade is the core element of an evaluation protocol designed to produce reliable data for adaptable water resources governance in China. The research findings in this study will also be integrated into the new national standard to be issued by the Ministry of Water Resources of China in late 2020.

Keywords: freshwater health; river chief system; ecological integrity; social services; water governance; national standard

1. Introduction

There has been a longstanding recognition of the need for maintaining and improving the status of freshwater ecosystems across the world. Freshwater resources, mainly consisting of rivers and lakes, are closely related to not only the natural environment but also the human society as well as how human beings are engaged with the environment. The United Nations' Sustainable Development Goal 6 (SDG6), 'Clean Water and Sanitation' [1] sets goals of ensuring global water access and safety by 2030 by investing in adequate infrastructure and protecting and restoring water-related ecosystems. SDG 6 recognizes that water has multiple values and that they are all related, i.e., the success in one may depend on another. For example, a healthy freshwater ecosystem entails not only good water quality (less pollution) and low water stress (reasonable consumption), but also the improved water governance. This worldwide consensus was reached after decades of exploration and efforts made by many countries to find a well-balanced combination of 'led-by-science' and 'led-by-administration', while this exploration still continues.

The well-known Clean Water Act of 1977 was enacted in response to the dramatic pollution in the 1970s in the USA and is the world's first comprehensive and systematic environmental law for managing freshwater health [2]. Since the 1990s, researchers have contributed to developing advanced freshwater health frameworks beyond the original non-modern working modes; and the governments of many countries are working with scientists and the public to explore innovative approaches. For example, the European Water Framework Directive 2000 (WFD) was a valuable attempt to establishing a large transboundary cooperation framework, although the outcomes are not satisfactory in some aspects due to the unrealistic timeframe and the lack of functional indicators [3,4]. The flawed performance of the WFD also highlights the importance of a system with consistent administrative supervisions and enforcements; for example, the United Kingdom, even Scotland itself, have their own detailed assessment approaches [5–7]. In New Zealand and Australia, officials and scientists have also been aware of the urgency and made remedial efforts to upgrade the existing protocols [8,9].

Understanding the meaning of river (lake) health is another obstacle for countries with goals of sustainable development. Many researchers have been describing and debating the concept of river (lake) health since the 1990s [10–14]. As usefully defined by Meyer [15], a healthy water body can keep its ecological functions while maintaining the needs of the society. The models proposed by Boulton and Lackey [12,16] provided an important point of view that the human use of rivers does not automatically mean that the ecosystem health is being degraded. A healthy river (or lake) should contain both ecological values (ecological integrity and resilience to stress) and human values (social services and benefits). Therefore, ecological integrity is one part of a healthy ecosystem but not the only part; the lack of human values might also be detrimental. Usually, ecological integrity includes the physical, chemical, and biological components [17] and has long been treated as the major (sometimes the only) aspect of freshwater assessments. Obviously, incorporating social indicators is of significance, as detailed by Hanna et al. [18].

In the past decades, the health status of rivers and lakes in China has undergone significant deteriorations due to urban development and the increasing water use. Severe outcomes, e.g., water pollution, hydrologic mutation, the damaged physical structures, and the degenerated ecological diversity and functions, have attracted wide attention from governments and researchers. For example, in the 2000s, the water pollution in Guangdong Province, one of the most prosperous region in China, significantly affected the sustainability of the regional social economy while was rarely contained by local officials [19]. The outbreak of blue-green algae in Wuxi, Jiangsu Province, in 2007 eventually pushed the central government of China to establish a nation-wide system to contain pollution with a consistent protocol [20]. This is the origin of the River Chief System (RCS) known by the public nowadays. Since 2016, China has been fully implementing the RCS to build an efficient and productive framework that involves not only administrative innovations but also refined scientific guidelines to ensure the adequacy of specific evaluations. The principle of the RCS is using a hierarchical administrative structure with well-defined responsibilities and accountabilities to avoid the inaction of officials at different levels. Therefore, evaluating and improving freshwater health in China has become an issue with intertwined political and scientific drivers that make the original working models much less effective than expected. At the moment, China is still lacking a comprehensive evaluation framework due to the vast regional differences and the insufficient administrative experience of managing the massive RCS system. This study is conducted based on the request of the Department of River and Lake Management of the Ministry of Water Resources of China in 2019. As stated, it is essential to clarify the meaning and criteria of river/lake health and propose a systematic approach that fits for the characteristics of the RCS to improve the freshwater health in China.

The objectives of this paper include: (1) Reviewing the relevant research on the RCS comprehensively and providing a clear picture of its working mechanism; (2) comparing the best practices in China and the rest of the world to highlight the key aspects that are ignored and the lessons learnt; (3) analyzing the existing freshwater health indicators adopted by researchers and practitioners to help understand their strengths and weaknesses; and (4) proposing a new evaluation framework for the future implementation

within the framework of the RCS in China. The achievement made in this study will be integrated into the new national standard to be issued by the Ministry of Water Resources of China. The specific methods for field sampling and data collection, aggregation, harmonization, and integration are beyond the scope of this paper.

2. Methodology

The literature review in this study is mainly focused on two aspects: The research on the RCS in China, and the research and application of freshwater health indicators both in China and around the world. Regarding the RCS, only published materials in English are reviewed in this paper to reach a wider audience. Nevertheless, a large number of scholars in China have made significant contributions by publishing articles in Chinese, which are recommended to be read extensively, if possible, for a better understanding of the development of the RCS. Regarding freshwater health indicators, the authors have collected most of the systematic and well-structured regional standards/guidelines in China, which are either formal documents or unpublished drafts, by extensive data search and enquiry. Data sources without a clearly defined indicator framework are not included. International frameworks reviewed in this paper are restricted to those that have significant influence across the world and have been well studied and improved. Therefore, the selected frameworks include the European WFD and those applied in major English speaking countries, including the USA, the UK, Australia, New Zealand, and Canada. The practices of other countries or regions are also reviewed but not included. The indicators used by the reviewed materials are further summarized and analyzed later in this paper to produce a new evaluation framework. In regard to data integration, similar categories, sub-categories, or individual indicators that have different names are compared carefully in terms of their definitions, and only the most widely adopted names are kept to avoid confusing readers. For example, the term 'physical habitats' is used to replace all the similar terms like 'forms' or 'physical environments'; nitrogen-related indicators, e.g., total nitrogen and dissolved nitrogen, are all replaced by the generic term 'nitrogen'.

The methodology of this paper is also subjected to limitations. The detailed approaches to determine the characteristic value of each indicator are not addressed so that this paper intends to provide an overview of freshwater health evaluation instead of technical instructions. Furthermore, the practical experience gained in the developed world, as well as the working model of the RCS, might not be suitable for less developed countries or regions, as the tradition and awareness of preserving water resources differ, and their needs for boosting economy are much more urgent. We argue that protecting water resources and ecosystems does not automatically entail the sacrifice of economic development, and it is also inequal to enforce the same level of restrictions to countries of different levels of prosperity. More efforts should be made to facilitate the coordination of global sustainable development under the framework of the UN's SDG6.

3. River Chief System (RCS) in China

3.1. Recent Literature in English

The implementation of River Chief System has facilitated the effective integrated freshwater management and water protection campaigns in China in the last decade and also attracted extensive research interests both domestically and internationally. Dai [21] introduced the history of the River Chief System and provided a perspective to the water governance in China as well as what role formal laws have played during the transition to the RCS. Huang and Xu [22] argued that the public participation of RCS mainly depends on local government, which, although ensures effective integration of resources, might impede the real public participation and supervision due to the political complexity of water governance in China. Wang et al. [23] stated that, although RCS can improve the work efficiency of water governance in the short-term, more efforts are still needed to the problems of organizational logic and the responsibility dilemma that remain due to the persistence of vertical coordination of the

hierarchical system. Liu and Richards [20] summarized the structure of the RCS and the progress of implementation and identified future challenges. Similar to Wang et al. [23], Liu and Richards [20] also pointed out the flaw of the existing RCS regarding trans-regional collaboration and accountability. Liu et al. [24] presented a case study of Foshan in Fujian Province and showed that the RCS could establish a considerably sophisticated and effective management structure. More recently, Wang and Chen [25] argued that the institutional context and motivations are the external conditions influencing the collaborative governance regime and thus the outcomes of the RCS. In general, numerous studies in recent years have noticed and identified the internal flaws of the existing RCS that may influence its sustainability and efficacy in the long-term. Compared with the water governance policies in many other western countries (e.g., USA, UK, Australia, and New Zealand), the political and administrative complexity of China makes it necessary to come up with a more structured and practical approach to management the River/Lake Chiefs at different levels and assess their performances.

3.2. Policy

As summarized by Wang and Chen [25] the institutional context of China contains three major elements: The centralized political authority [26], the party-state hierarchy [27,28], and the cadre responsibility system [29]. This context enables the central government of China to play the role of ‘policy issuer’ while maintaining sufficient authority of enforcement at different administrative levels through a top-down performance assessment structure. Since the full implementation of the RCS in 2016, the central government (mainly the Ministry of Water Resources) has issued multiple instructive documents in regard of the responsibility, accountability, major problems to be addressed, and the principle of assessing the performance of Chiefs [30–32]. Meanwhile, the local governments (mainly in provincial level) are responsible for making their own regulations under the prescribed framework due to the absence of national legislation for the RCS. In contrast, many western countries tend to leave water resources management relying on a relatively flat structure by establishing managerial agencies at the level of individual river basins, which is partly due to the lack of central authority. For example, the European WFD provides motivations to initiate waterways monitoring programs as well as directions for its EU member states on data processing and reporting so that their results will be comparable. However, the duties of managing specific river basins, e.g., Rhine River Basin, still belongs to relatively independent organizations like The International Commission for the Protection of the Rhine against Pollution (ICPR), which is co-chaired by ministers from stakeholder countries. This working model is more about cross-border collaboration and coordination and is obviously not suitable for China that needs a well-defined procedure for top-down supervision.

3.3. Assessing the Performance of Chiefs

By the end of 2018, RCS had been established and fully implemented in all the 31 provinces and regions in China with over 300,000 River (Lake) Chiefs being appointed at provincial, municipal, county, and township levels. Thus, as mentioned above, it is necessary to build a comprehensive and effective approach to assess the performance of those River (Lake) Chiefs, and this approach is much different to the assessment of freshwater health itself that is mainly determined by scientific criteria. More considerations are raised due to the political and administrative complexity of the RCS. The transition from ‘rule by men’ to ‘rule by law’ [25] entails not only assessing to what extent the RCS has been established and supervised by the heads in different administrative levels, but also how intertwined scientific and political requirements are satisfied during this implementation process. Therefore, a practical and straightforward assessment approach was urgently needed and have been proposed accordingly based on the existing outlines [33], as summarized in Table 1. This approach was officially released in 2019, and, together with the freshwater health scoring approach to be discussed later in this paper, comply well with the principle of using quantifiable measures for assessments. We also believe this approach can be well applied in other countries after adaption.

Table 1. The approach to assessing the implementation of the River Chief System (RCS) with detailed scoring criteria.

No.	Tier-1 Categories	Tier-2 Categories	Scoring Criteria
I	Building RCS hierarchy and organizations (25 points)	1. Establishment of RCS heads in provincial, municipal, county and township levels. (4/25)	<ul style="list-style-type: none"> Establish provincial Chiefs and announcement (newspaper, television, internet, etc.) (1/4) Establish municipal, county and township Chiefs and announcement (newspaper, television, internet, etc.) (3/4)
		2. Establishment of River Chiefs and announcement. (9/25)	<ul style="list-style-type: none"> Duty assignment for rivers/lakes in provincial level and announcement (newspaper, television, internet, etc.) (3/9) Duty assignment for rivers/lakes in municipal, county and township levels and announcement (newspaper, television, internet, etc.) (6/9) Deduct all the Establish provincial Chiefs and announcement (newspaper, television) scores if any one of the River (Lake) Chiefs is not established properly.
		3. Establishment of RCS offices and administrative system. (9/25)	<ul style="list-style-type: none"> Employment of full-time and part-time RCS staff with a valid contract; staff in position. (6/9) Sufficient work fund. (1/9) Appropriate workplace and signage (2/9)
		4. Set-up of RCS information notice boards. (3/25)	<ul style="list-style-type: none"> Notice boards showing the duties and information of River (Lake) Chiefs, basic conditions of rivers/lakes, and contact information. (3/3) Spot check shall be performed for at least ten sites; information should be updated up to one month after the appointment of new chiefs.
II	Building RCS regulations and mechanism (15 points)	5. Establishment of RCS regulations in provincial, municipal and county levels. (4/25)	<ul style="list-style-type: none"> Establish, announce and implement RCS rules in provincial, municipal and county levels, including chief meeting, information sharing, information reporting, supervision, accountability/incentives, and acceptance inspection.
		6. Establishment of organizational mechanism (8/25)	<ul style="list-style-type: none"> Coordination mechanism between different departments. (4/8) Public participation (supervision, volunteering, photographing, education, scientific popularization, etc.). (2/8) Capital investment mechanism. (2/8)
		7. Determination of responsibility and accountability (3/15)	<ul style="list-style-type: none"> In provincial level. (1/3) In municipal and county levels. (2/3)
III	Duties performed by River Chiefs (12 points)	8. Main issues (8/12)	<ul style="list-style-type: none"> RCS meeting for work deployment and actions (4/8) RCS meeting for coordinating main issues and supervision. (4/8)
		9. Daily issues (4/12)	<ul style="list-style-type: none"> Sufficient patrol and inspection; problems are spotted and addressed. (2/4) Appraisal of subordinate chiefs and RCS departments. (2/4)

Table 1. Cont.

No.	Tier-1 Categories	Tier-2 Categories	Scoring Criteria
IV	Organizational works (16 points)	10. Supervision and appraisal (6/16)	<ul style="list-style-type: none"> Supervising subordinate chiefs and RCS department; works are improved; inaction and default are punished. (3/6) Appraisal scheme is available; outcome is considered when assessing the performance of local government. (3/6)
		11. Basic works (6/16)	<ul style="list-style-type: none"> Compiling, printing and issuing RCS policy documents in provincial level. (2/6) Establishment of river/lake archive. (1/6) Establishment of the RCS information system. (3/6)
		12. Publicity and training (4/16)	<ul style="list-style-type: none"> Publicity in provincial, municipal and county levels (television, internet, newspaper, social media, etc). (2/4) Training of RCS staff at different levels. (2/4)
V	The outcome of water protection and management (32 points)	13. Water quality of rivers, lakes and centralized drinking water sources (9/32)	<ul style="list-style-type: none"> The ratio of surface water areas of good quality meets the national criterion. (3/9) The ratio of surface water areas of bad quality meets the national criterion. (3/9) The ratio of drinking water sources (municipal level or beyond) of good quality meets the national criterion. (3/9)
		14. Remediation of odorous urban water (4/32)	<ul style="list-style-type: none"> Over 90% of odorous water bodies in urban areas are eliminated. (4/4)
		15. Protection of shoreline and riparian zone (9/32)	<ul style="list-style-type: none"> Over 80% of illegal occupation, mining, piling and construction are eliminated; works accomplished are archived; appropriate shoreline and riparian management plan are available. (6/9) Administrative zones are determined. (3/9)
		16. Integrated management of ecosystem (5/32)	<ul style="list-style-type: none"> Integrated ecosystem remediation works are implemented at the provincial level. (2/5) Contamination management of aquaculture, rural waterway and waste, and livestock breeding. (3/5)
		17. Public satisfaction (5/32)	<ul style="list-style-type: none"> Public satisfaction >90% (5/5); >80% (4/5); >70% (3/5); >60% (2/5); >50% (1/5); <50% (0/5).

4. Integrated Indicator Framework

Evaluating the health status of freshwater also heavily relies on the establishment of a practical and comprehensive scientific framework based on the best practices around the world. In this study, we aim to investigate how ecological and non-ecological indicators are adopted and incorporated in different regions of China and other major western countries with substantial experience. A comprehensive data and literature research are therefore conducted and will be presented in detail in this section.

4.1. Data Sources

Although the River Chief System has already been established across the country, the lack of a nation-wide operational standard forced the local government to resort to their existing experience or routines for implementing assessments; those routines usually show enormous inconsistency and even contradiction sometimes. Currently, only a few standards have been issued officially in provincial or municipal levels, while some other regions still rely on “drafts”, “trial documents”, or informal manuals that are subjected to many limitations. Table 2 summarized the existing regional standards, guidelines, and specifications being used in China [34–48]. Furthermore, we also reviewed the frameworks implemented in some major western countries for comparative analysis, such frameworks including the United States (National Aquatic Resources Surveys (NARS)) [49–51], New Zealand (Cawthron’s Freshwater biophysical ecosystem Health Framework) [9], Australia (Integrated Ecosystem Condition Assessment) [8], and the United Kingdom (Common Standards Monitoring Guidance for Rivers/Lakes) [5,6]. Some other national or regional frameworks known by the public (e.g., Canadian Aquatic Biomonitoring Network (CABIN), the Murray-Darling Basin Sustainable Rivers Audit of Australia, and the National Environmental Monitoring and Reporting of New Zealand) are also reviewed but are not included in this section as they only focus on limited aspects of freshwater health or are relatively outdated and have been superseded in their own countries. More details can be found in [52–55] regarding those frameworks. It should also be noted that although the European Water Framework Directive (WFD) streamlines the legislation across Europe and provides guidance to member states on what component indicators are necessary (i.e., biological quality, hydro-morphology, and physicochemical attributes), the implementation is still inconsistent and varies widely from country to country. Therefore, in this study, we only selected the UK guidelines as representatives as they have been widely accepted and well examined. The overseas frameworks included in Table 2 are the best practices in the corresponding countries and have been well revised and modified for better effectiveness.

Table 2. The national, regional, and industrial standards, guidelines, and specifications used for summarizing the existing freshwater health indicators.

Source	Abbr.
Local Standard of Beijing City: DB/11T 1722/2020 Technical regulations for ecological health on aquatic ecosystem assessment [34]	DB11
Local Standard of Liaoning Province: DB21/T 2724/2017 Liaoning provincial evaluation guidelines for river and lake (reservoir) health [35]	DB21
Local Standard of Jiangsu Province: DB32/T 3674-2019 Specification for ecological river and lake status assessment [36]	DB32
Local Standard of Suzhou City: DB3205T 2019 Indicator system of river and lake health assessment (Unpublished draft) [37]	DB3205
Local Standard of Shandong Province: DB37/D 3018-2017 Shandong provincial evaluation standard for ecological river [38]	DB37
Report of Zhejiang Institute of Hydraulics and Estuary Evaluation of main rivers and lakes in Zhejiang Province [39]	ZJ

Table 2. Cont.

Source	Abbr.
Report of Fujian Normal University: Indicators and methods for assessing river health in Fujian Province [40]	FJ
Report of Guizhou Normal University: Guideline for assessing river (lake) health in Guiyang City [41]	GY
Standard of China Association for Engineering Construction Standardization: Technical Guidelines for Evaluating Water Quality of Urban Rivers and Lakes (draft) [42]	CECS
Draft of Ministry of Water Resources (for consultation purpose): Guideline for river and lake health assessment [43,44]	SL
Report of Ministry of Water Resources: Indicators, standard and method for assessing river and lake health (for pilot work) [45]	2010
“Happy River” indicators of Ministry of Water Resources (internal documents)	XFH
The United States Environmental Protection Agency: National Aquatic Resource Surveys [49–51]	USA
Cawthron Institute report prepared for Ministry for the Environment, New Zealand: Freshwater Biophysical Ecosystem Health Framework [9]	NZ
Australian Department of the Environment and Energy: Aquatic Ecosystems Toolkit. Module 5: Integrated Ecosystem Condition Assessment [8]	AU
The United Kingdom Joint Nature Conservation Committee (JNCC): Common Standards Monitoring Guidance for Rivers/Lakes [5,6]	UK

4.2. Key Components of an Evaluation Framework

After reviewing the documents listed in Table 2, we summarized the core components of a freshwater health framework, as shown in Table 3. The definition of a healthy freshwater ecosystem in New Zealand is stated by the National Policy Statement for Freshwater Management (NPS-FM) [56] as that reflects the importance of physical and chemical as well as biological elements of ecosystems. In the United States, NARS divides the basic indicators into four categories: Biological, physical, chemical, and recreational; the last category is a measurement of the pathogen and pollutant substances that can threaten people’s wellbeing during recreational activities. The UK and Australian guidelines [5–8] further introduced more indicators in regard to social services; the former concerns more about the direct disturbance to human beings while the latter about the social functions and values provided. In general, biophysical ecosystem health can be represented by a measure of ‘ecological integrity’ [9], but it is only one part of an assessment of the ability of a freshwater ecosystem to support multiple freshwaters values. Even for ecological integrity itself, a well-balanced assessment cannot be achieved by a single biophysical measure because an ecosystem is a complex network of interacting biological communities and their physical environment. Therefore, the core components of a freshwater health framework should include the following sectors: Aquatic life (fauna, flora and microbes), water quality (physio-chemical features and pathogens), water quantity (hydrology), physical habitat (forms), ecological processes, and, as mentioned above, social services and values. Specifically, “ecological processes” are the interactions among aquatic lives and their environment and can be represented by a series of individual indicators in other categories to suggest the status of dynamic biochemical processes [57,58]. The assessment of ecological processes entails advanced knowledge and experience and may be relatively more difficult than other categories.

It should also be noted that, as discussed previously, the unique administrative hierarchy in China make freshwater health a political mission that is directly related to the performance of local officials. Therefore, water governance indicators should also be included in this framework with quantifiable items and practical calculation methods.

Table 3. Indicator categories of a freshwater evaluation framework and definitions.

Category	Criteria for Being “Healthy”	
Ecological integrity	Physical habitat	The physical form and extent of the water body and the surrounding riparian areas are capable of supporting diverse flora and fauna throughout their life cycle.
	Water quality	The physical and chemical properties as well as other components of the water body are in natural status and may support diverse flora and fauna. For example, contaminants are scarce or absent.
	Water quantity	The water level, extent and flow regime are sufficient to support diverse flora and fauna during their full life cycle. As defined by Clapcott et al. [9], ‘flow regime’ includes the floods and droughts that ensure the surface water connectivity between the fresh waters and surrounding terrestrial habitat and other freshwaters (e.g., rivers and their floodplains, and wetlands), the regulation of biotic production and diversity, and that shape the morphology of physical habitat.
	Aquatic life	A diverse range of native species of flora and fauna persist; invasive alien species are scarce or absent; rare native species can be seen.
	Ecological processes	The normal interactions among aquatic lives and their environment persist (e.g., metabolism) with an optimized level of organic matter cycling, e.g., the retention, transformation and uptake of carbon and other nutrients.
Social services / values	A healthy water body can provide a wide range of non-ecological functions and benefits to human beings and the society, including cultural services (e.g., recreation and aesthetic beauty), provisioning services (e.g., water supply and aquaculture), regulating services (e.g., flood protection), etc.	
Water governance	A healthy water body entails a set of managerial protocols that can effectively facilitate the implementation of specific water protection activities and more efficient water governance in different administrative levels.	

4.3. Comparison

Table 4 shows the detailed comparison of indicators used by the standards and guidelines summarized in Table 2. The following issues should be noted:

- For the four overseas frameworks included, only the Australian guideline introduced social service indicators. The recreation indicators used by NARS are actually still biological and physio-chemical indicators or pathogens and could be more reasonably integrated into those corresponding categories.
- Many standards in China (e.g., Jiangsu, Shandong, Fujian, and Suzhou City) suggest referring to other national standards (GB3838-2002: Environmental quality standards for surface water; SL395-2007: Technological regulations for surface water resources quality assessment) for instructing water quality assessment. We also recommend this approach as those two water quality standards have been well examined during practices.
- “Ecological processes” is a relatively abstract and unintuitive concept compared with other categories and is only recommended by New Zealand’s framework. Each ecological process can actually be represented by the values of specific physio-chemical or biological indicators, e.g., nutrient loads and BOD₅.
- Zoning indicators include: (1) The classification of water function zones that will be discussed later in this paper; (2) the clarification responsibilities; (2) and (3) the implementation of water quality management in different water function zones.

By comparison, we find that 11 indicators are mentioned over 10 times, including riparian vegetation coverage, dissolved oxygen, eco-water (environmental flow), water mobility and connectivity, riparian naturalness, macroinvertebrate, phosphorous, ammonia or nitrate, heavy metals, flood protection, and zoning indicators. The most significant distinction between Chinese standards and overseas frameworks will be further discussed in the following section.

Table 4. Comparison of indicators of different frameworks, guidelines, and regional specifications. The dots show in which framework the indicators are adopted.

Category	Sub-Category	Indicator	DB11	DB21	DB32	DB3205	DB37	ZJ	FJ	GY	CECS	SL	2010	XFH	NZ	AU	UK	USA	Total	
Physical habitat	Shape	Bank/channel form & stability		●		●		●		●		●	●		●	●	●		9	
		Substrate stability														●				1
	Substrate	Substrate composition														●	●	●	●	4
		Substrate contamination					●	●					●				●			4
	Connectivity	Water mobility & connectivity	●	●	●	●			●	●			●	●		●	●	●		11
		Instream structures												●				●		2
	Riparian	Riparian naturalness	●	●	●	●				●	●		●	●		●	●	●		11
		Riparian vegetation coverage	●	●	●	●		●	●	●	●		●	●	●	●	●	●	●	15
	Other	Naturalness of water area & form			●	●	●										●			4
		Erosion & sedimentation		●					●				●		●		●	●		6
		Debris															●	●		2
		Wetland status							●				●		●					3
		Habitat extent & structure														●			●	2
Water quality	Physical	Temperature	●										●		●				3	
		Dissolved oxygen	●	●	●	●	●		●	●	●		●	●	?	●	●	●	●	13
		Conductivity																	●	1
		Clarity/turbidity	●							●		●				?	●	●		6
		Sediment load													●	●		●		3
		Salinity	●													?	●		●	3
		Oxidation Reduction Potential										●								1
	Chemical	pH & acidity	●		●	●	●		●						?	●	●	●	●	9
		Nitrogen	●		●	●	●		●	●					?	●		●	●	9
		Phosphorous	●		●	●	●		●	●					?	●	●	●	●	10
		Ammonia or nitrate	●		●	●	●		●	●	●			●	?	●		●		10
		Permanganate	●		●	●	●		●	●				●	?					7
		Oxygen needs (COD, BOD ₅ , etc)		●	●	●	●		●	●				●					●	8
Other	Other organic composites																●	●	2	
	Nutrient loads		●					●				●		?	●	●			5	
	Trophic diatom																●	●	2	
	Heavy metals		●	●	●	●		●	●				●	?	●		●	●	10	
	Chlorophyll a	●							●					?		●	●		4	
	Sulfide			●	●	●		●						?					4	
Other (cyanide, fluoride, etc)			●	●	●		●								●			5		

Table 4. Cont.

Category	Sub-Category	Indicator	DB11	DB21	DB32	DB3205	DB37	ZJ	FJ	GY	CECS	SL	2010	XFH	NZ	AU	UK	USA	Total	
	Pathogen	E. coli			●	●	●		●					?					4	
		Enterococci																	●	1
Water quantity	Magnitude	Water depth & area	●									●			●		●		4	
		Water volume															●			1
		Discharge & velocity													●	●		●		3
	Flow	Eco-water (environmental flow)		●	●	●	●	●	●	●			●	●	●		●	●		12
		Mean (annual) flow														●				1
		Long-term and seasonal variability		●					●		●		●	●		●	●	●		8
	Flood and drought	Flood occurrence														●				1
Drought occurrence																●			2	
Aquatic life	Fish	●	●				●		●			●	●		●			●	8	
	Benthonic (macro)invertebrate	●	●	●	●					●		●	●		●	●	●	●	11	
	Macrophytes	●						●				●			●	●	●	●	7	
	Periphyton			●	●										●			●	4	
	Plankton	●		●	●					●		●				●		●	7	
	Microbes														●			●	2	
	Waterbirds		●				●	●	●						●	●			6	
	Terrestrial animals		●													●			2	
	Fauna diversity								●									●	2	
	Invasive species									●				●				●	3	
	Rare species													●		●	●		3	
	Social service	Flood protection	●	●	●	●	●	●	●	●			●	●	●		●			10
Shipping & navigation								●											1	
Water supply & consumption				●	●				●			●		●		●			6	
Scenic & aesthetic					●	●	●												3	
Culture & history			●				●	●								●			4	
Recreation & tourism																●		●	2	
Sensory & human comfort					●	●	●												3	
Public satisfaction			●	●	●	●	●	●	●			●	●						8	
Agriculture & food supply													●	●		●			3	
Industrial benefit														●					1	

Table 4. Cont.

Category	Sub-Category	Indicator	DB11	DB21	DB32	DB3205	DB37	ZJ	FJ	GY	CECS	SL	2010	XFH	NZ	AU	UK	USA	Total	
Water governance		Zoning & zonal status		●	●	●	●	●	●	●		●	●	●					10	
		Professional team & plan						●											1	
		Disturbance to society			●	●	●	●					●					●	●	7
		Utilization of water resources		●				●	●	●	●		●	●						7
		Facility, instruments & signboards						●												1
		Sewage regulation				●	●	●												3
		Illegal activities				●	●	●												3
Ecological processes		Biota interaction & food web													●				1	
		Ecosystem metabolism													●			●	2	
		Organic matter processing													●				1	

4.4. Indicators Highlighted

Based on the comparison of detailed indicators shown in Table 4, the major difference between those widely used in China and in major western countries are mainly non-ecological indicators, e.g., social services and water governance indicators. This difference is attributed to the different social cultures and administrative structures between China and western countries. The adoptions of ecosystem-related indicators are generally similar and consistent, as mentioned in the last section. This section discusses the details of those discrepancies as well as how those indicators are adapted in China.

4.4.1. Indicators of Social Services and Values

Current frameworks used by major countries across the world have paid much attention to ecological values when evaluating the health status of rivers, lakes, and wetlands. In contrast, very few countries have made attempts to include human values. The Australian Integrated Ecosystem Condition Assessment (IECA) [8] recommends to include cultural, regulating, and provisioning services in the evaluation process but does not provide detailed indicator sets. The National Aquatic Resource Survey (NARS) of the United States [49–51] uses four indicators (Algal toxins, Cyanobacteria, Enterococci, and fish tissue contaminants) to assess the status of recreational functions, but does not pay much attention to the broader concepts of human values. In general, although a few studies have emphasized the importance of social services, more works are still needed to convert the existing research accomplishments of scientists to guide the actions of governments and authorities.

The first systematic attempt to define human services was made by the Millennium Ecosystem Assessment [59]. In this report, ecosystem services are divided into four categories, including cultural ecosystem services, provisioning ecosystem services, regulating ecosystem services, and supporting ecosystem services; the first three categories resemble those prescribed by the Australian IECA guideline. Specifically, cultural ecosystem services include non-material benefits such as recreational activities (e.g., swimming), the aesthetic beauty of rivers, and their spiritual significance among many communities. Provisioning ecosystem services include the products obtained, e.g., drinking water supply, fish, etc. Regulating ecosystem services include the benefits obtained from the regulation such as erosion prevention, pollution reduction, and flood protection. Furthermore, supporting ecosystem services include processes that help the production of other services, such as nutrient cycling and habitat provision, which are closely related to specific water quality indicators. As a recent and representative study, Hanna et al. [18] systematically reviewed 89 relevant studies and summarized the human services provided by rivers. It is found that the most studied and discussed social services are recreation and tourism and water supply that can provide visible monetary benefit. Regarding the categories, provisioning and regulating indicators have been much more studied than the other two categories (cultural and supporting). However, in China, more attention has been paid to flood protection engineering and public satisfaction as those measures can be more easily quantified and related to the performance of officials. Therefore, it is essential to combine the most emphasized indicators both in China and overseas to build a refined social services indicator set.

4.4.2. Indicators of Water Governance

As mentioned previously, one distinct feature of evaluating freshwater health in China is the close connection between science and politics. The establishment of the River Chief System facilitates the clarification of the responsibility and accountability of local government officials, who, however, lack the necessary scientific background and expertise to actively engage with and manage the specialist teams and track their performances. The political structure and hierarchy in China could not grant sufficient authority to any stand-alone managerial committee that supervises the condition of specific water bodies. Therefore, introducing a set of water governance indicators is obviously necessary and may assist the local RCS heads (i.e., Chiefs) to involve with the detailed scientific programs in a practical and concise way.

One of the most typical water governance indicators is the water condition in different water function zones, which enable the RCS heads to gain a general understanding of the spatial-temporal distribution of health status without going through too many details. The definition of water function zones in China is prescribed by the Ministry of Water Resources [60] according to the purpose of water usage, as shown in Table 5. Many existing standards in China (see Table 4) only implicitly prescribed that “water quality status should meet the criteria in different water function zones”. The criteria in Table 5 should be widely used for the classification of main water areas in China and clearly suggest the suitable working objectives of Chiefs in different regions.

Other water governance indicators in Table 4 are also closely related to the operation of the RCS and are rarely used by common guidelines oversea.

4.4.3. Indicators of Ecosystem Resilience

The definition of resilience shows significant ambiguity regarding the restoring capability of an ecosystem and usually to some extent overlaps with some other individual indicators that can be more explicitly measured or quantified. Resilience is a measure of persistence; ecological resilience measures the magnitude of disturbance that a system can absorb before it undergoes changes in structure and function [61]. As stated by Davies et al. [54], ecosystems incorporate the properties of the living and non-living components with “emergent properties”, e.g., diversity and resilience. Those properties are more like attributes of the system rather than its components and cannot be directly observed or measured intuitively. A typical ecosystem health monitoring may examine components and processes that are sensitive to disturbances over a range of spatial-temporal scales [13]. Those disturbances might include losses of native flora and fauna, and the invasion of alien species may further complicate the conditions. For example, Scotland’s Environment Protection Agency (EPA) uses the condition of peatland and the number of a few alien species (e.g., grey squirrel and American mink) to determine the recovery capacity of an ecosystem. Another approach is to monitor the products of ecological processes operating over a range of scales [62], e.g., dissolved oxygen and chemical oxygen demand (COD), which are also key components of water quality monitoring. Although being of scientific significance, using resilience indicators needs balanced scientific judgement and may unnecessarily complicate the evaluating process. The tradeoff between science and administration is one of the core components of the RCS, and thus the formal application of resilience indicators might not be suitable but can provide supplementary information for experts.

4.4.4. Eco-Water (Environmental Flow)

Eco-water, or environmental flow, is another key indicator to measure the level of satisfaction of water quantity needed for maintaining the basic ecosystem functions and processes. A large number of studies has been published in recent two decades regarding this topic. Tharme [63] provided a comprehensive review of the concept of environmental flow as well as the existing environmental flow methodologies around the world. The methodologies can usually be divided into four categories: Hydrological, hydraulic rating, habitat simulation, and holistic methodologies. Specifically, hydrological methodologies that rely on arbitrary low flow indices are the most widely applied and easy-to-use category. Kuriqi et al. [64,65] provided new insights into the interaction between hydropower energy yields and environmental flow, as well as the needs for maintaining the balance of the ecosystem. Although the European WFD does not use the term “environmental flow” explicitly, the required biological status can only be achieved when the necessary hydrological regimes are maintained [66]. The UK also has set environmental standards for water abstraction limits and appropriate water release from reservoirs. Poff and Zimmerman [67] reviewed the relevant publications in the last decades and emphasized that the risk of ecological deterioration may increase with increasing magnitude of flow alteration. Many studies [68–70] have also paid attention to the significance of environmental flow for water governance.

Table 5. The definition and classification of water function zones under the framework of the RCS in China.

Tier-1 Category	Tier-2 Category	Description
Protection zone		A protection zone is a water area of significance for the protection of water sources, drinking water, nature reserves, scenic locations, and the protection of rare and endangered species. It is prohibited to build, rebuild, expand, or engage in water-related activities that are not related to protection within the core areas of nature reserves and tier-1 water source areas.
Reservation zone		A reservation zone is a water area reserved and protected for future development and water resources utilization. Activities that may have a significant impact on water quantity, water quality, and water ecology should be strictly limited and managed.
Buffer zone		A buffer zone is a water area designated for the following purposes: (1) coordinating water-use relations among provinces and areas with prominent conflicts of benefit; (2) connecting inland/marine zones and protection/development zones that are designated for different purposes. In a buffer zone, all types of water-related activities should be strictly managed to prevent adverse effects on adjacent water function zones. All water-related activities that may be detrimental to the protection of water functional areas in the buffer zone at the provincial boundary shall be notified to the basin management agency in advance.
Development zone	Drinking water zone	A drinking water zone is a water area delimited or reserved for providing drinking water for urban and rural areas. In the areas that have been supplying water, further protection areas should be delimited for subsided water sources to preserved the water quality and volume. It is prohibited to build, rebuild or expand any types of sewage outfalls. In the areas reserved for future water use, the discharge of pollutants should be strictly controlled, and no new discharge into the river is allowed.
	Industrial water zone	An industrial water zone is an area designated to meet industrial water demand. Priority should be given to the specified water usage, and any type of water intake should be strictly managed. Any installation of sewage outfall should not influence the water quality required for the specified zonal functions.
	Agricultural water zone	An agriculture water zone is an area designated to meet the water demand for irrigation. Priority should be given to the specified water usage, and any type of water intake should be strictly managed. Any installation of sewage outfall should not influence the water quality required for the specified zonal functions.
	Fishery zone	A fishery zone is an area designated for protecting aquatic life (e.g., fish). The basic water demand for fishery should be maintained, and important physical environments (e.g., habitats for natural species, spawning beds, wintering beds, feeding grounds and migration passages) should be protected. Water pollution should be strictly controlled by the units and individuals engaged in aquaculture.
	Scenic and recreation zone	A scenic and recreation zone is the area designated to meet the needs of landscape, entertainment, and various leisure activities. Any activity shall not influence the water quality status in the area.
	Transitional zone	A transition zone is an area designated to connect adjacent function zones with different water quality requirements. Transition zone should be managed to guarantee the water quality in the downstream function zone. Any water-related activity that may damage the self-purification capacity of the water body should be strictly controlled.
	Sewage control zone	A sewage control zone is the area designated to receive intensive domestic and industrial wastewater while restraining the adverse impacts on the functions of downstream zones.

In China, most of the regional standards and guidelines reviewed in this study adopt eco-water/environmental flow methods to evaluate the health status of local rivers and lakes (see Table 4). Considering the difficulty of introducing complex methodologies within the framework of the RCS, a certain level of simplification is required. Currently, the standard issued by the Ministry of Water Resources of China [71] provides a simplified scoring method, based on the ratio of the minimum daily averaged discharge to the multi-year average discharge in the corresponding period. The final score is determined by calculating the lowest score in the periods of October to March and April to September, respectively. This approach, with the further involvement of aquatic life indicators, may reflect the local ecosystem-related hydrological conditions and is thus recommended to be carried on to the new framework.

5. Discussion

5.1. Lessons Learnt

5.1.1. Well-Defined Objectives and Motivations

A strong policy driver from authorities may provide the purpose for, and clear direction on, setting well-defined and descriptive objectives for regional water governance and specific monitoring and reporting activities. This driver is essential for maintaining the long-term sustainability and consistency of the existing framework. For example, the European Union's WFD has stated that the objectives are protecting and enhancing the health of aquatic ecosystems while successfully maintaining social and economic systems [72]. As requested, all European Union member states should achieve at least 'good ecological status' for all 'natural' water bodies by 2015 and at the latest by 2027. Although being too strict regarding the timeframe, the WFD's objectives have facilitated the comprehensive implementation of freshwater surveys and thus successfully obtained a large dataset for scientific judgement and further policy adjustment. In the USA, the objective of the Clean Water Act is restoring and maintaining the chemical, physical, and biological integrity of the waters, and thus the aims of the National Aquatic Resource Survey (NARS) is to provide robust data to help the corresponding assessments. In China, as defined by the central government, the main objectives of water governance at the current phase include mitigating human disturbance to water bodies (e.g., illegal mining, occupation, disposing, and constriction), enhancing local and regional regulations, and improving the public satisfaction and people's living quality. Therefore, the RCS was established accordingly to build a hierarchical administrative structure with clear responsibility and accountability. In general, the detailed approach for implementation should fit for the high-level goals set by authorities.

5.1.2. Comprehensive and Practical Indicator Metrics

Using a wide range of indicator metrics ensures that all essential aspects of ecosystem health are addressed. For those well-accepted frameworks outside China, biological (aquatic life) indicators are the core components that also reflect the need to measure the combined response to multiple pressures in a catchment. Those indicators are usually assessed in addition to water quality and habitat indicators and sometimes water quantity and ecosystem processes. As a result, the status of ecological integrity can be accurately assessed, but social values are rarely mentioned. In contrast, the previous practices in China overemphasized the importance of administration and management while not treating different aspects of an ecosystem as a dynamic entity.

Furthermore, during the establishment and implementation of the RCS in China in recent years, we found that the most complained part of the initial RCS framework is that the poorly trained local RCS heads had to be held accountable for what they did not fully understand. Overstretching the scientific aspect does not automatically lead to a better outcome.

5.1.3. A Standard Data Acquisition and Analysis Protocol

A standardized data approach ensures the consistency of evaluation results, which is crucial to the nation-wide implementation of the RCS. Some overseas frameworks (e.g., NARS and CABIN) are based on standardized approaches including field survey design, data collection and processing, and reporting. Some other frameworks (e.g., European WFD and the UN’s SDG 6) integrate data from different methods and make comparisons by data harmonization. In New Zealand and Australia, scientists have also been making efforts to establish standardized measurement protocols, but more works are still required on determining how to incorporate different components of river health into assessment programs in terms of network design and reporting [9]. Therefore, we intend to propose a functional and standardized protocol that is suitable for the RCS in China, which will be discussed in detail in the next section.

5.1.4. Adaptability

An adaptable framework is capable of adjusting or “upgrading” itself through a structured and iterative process that supports robust decision-making in the face of uncertainty. This feature is especially crucial for a country with typical hierarchical administrative structures that might cause unintended delay during decision-making. As a national standard, the indicator framework proposed in this study (see following sections) that is about to be officially issued this year will be reviewed and revised as a routine of two years.

5.2. A New Evaluation Protocol

As mentioned previously, a new protocol is proposed in this study to fit for the nation-wide implementation of RCS in China, which is displayed in Figure 1. This protocol is now going through the consultation process and will be officially issued by the end of 2020. Figure 1 shows the three core components of the protocol, including technical preparation, survey and monitoring, and report preparation. Specifically, “technical preparation” provides detailed instruction for preparing for field operation and data acquisition, and this sector is beyond the scope of this study. The following section will present and discuss the newly proposed indicator framework used as the core component of “survey and monitoring”. In addition, the results in the compiled final report will be concise and understandable to non-experts and can be used to support the assessment of Chiefs.

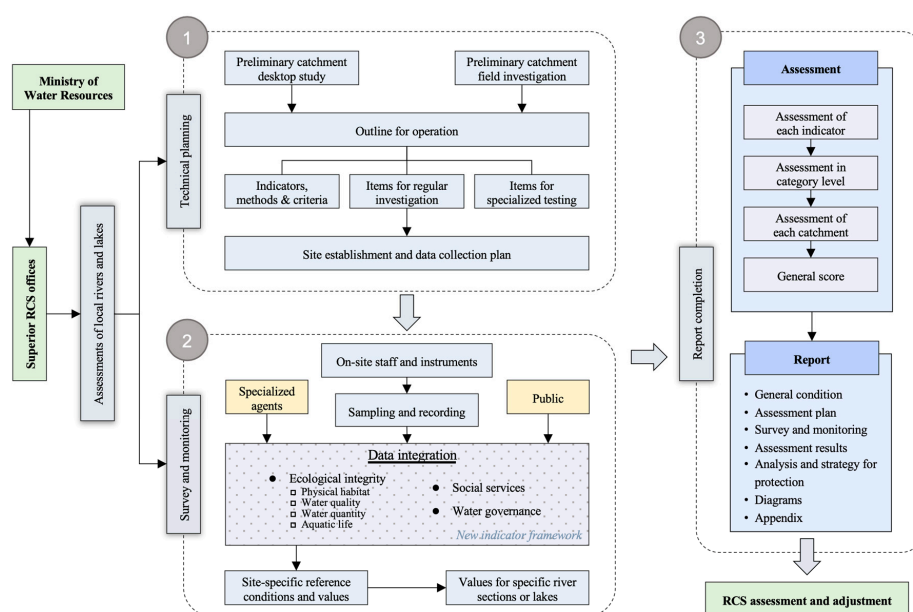


Figure 1. The new evaluation protocol proposed for nation-wide implementation in China.

5.3. Modified Indicator Framework

Table 6 summarizes the refined indicator framework to be adopted in China as well as the details of data sources and collection method. More specific sampling and testing methods are not discussed in this paper as they are beyond the scope of this study. It can be found that the indicators are classified into three main categories: ecological integrity, social service and water governance. Specifically, ecological integrity can further be classified into four sub-categories (physical habitat, water quantity, water quality and aquatic life) based on the existing experience and best practices around the world.

We recommend that the assessment of water quality follows the existing national standard implemented in China (GB3838-2002 and SL395-2007) [46,47] instead of building another new protocol, as the existing practices have been proved efficient with the reliable outcome. Specifically, GB3838-2002 [46] provides an extensive list of the substances (and threshold values) to be examined for general surface waters and, more importantly, centralized drinking water sources. The included items are more comprehensive than most of the overseas guidelines, and the testing can be conducted by the existing specialized agencies to produce concise reference reports for decision-making officials or Chiefs. SL395-2007 [47] provides an extra composite measure for lakes to determine the degree of eutrophication based on a series of individual water quality indicators (e.g., total nitrogen, total phosphorous, chlorophyll a, permanganate, clarity, etc). Those two standards have also been adopted by some pioneering provinces in China, e.g., Jiangsu, Shandong, and Fujian Provinces (see Table 4). Therefore, a seamless transition to the new nation-wide framework can be accomplished and save administrative resources significantly. Furthermore, the calculation of eco-water (environmental flow) demands can be made based on the existing standard [71]. The daily averaged discharge for rivers or daily averaged water level for lakes are compared with the calculated minimum demands to evaluate to what extent the necessary environmental flows are satisfied.

As shown in Table 6, weights (in parentheses) are assigned to each category and sub-category. A general health score will firstly be given to each selected river (lake) section. The determination of the score is based on weighted averaging approach. The equation can be expressed as:

$$RHI_i = \sum_{m=1}^m \left\{ WC_m \times \sum_{n=1}^n \left[WS_n \times \sum_{k=1}^k (WI_k \times G_k) \right] \right\} \quad (1)$$

where RHI_i = the general health score of the i th river (lake) section, W_k = the weight of the k th indicator, G_k = the score of the k th indicator, WS_n = the weight of the n th sub-category, and WC_m = the score of the m th category.

For the entire river or lake, the final score is averaged based on the score at each section, whose weights are determined by the corresponding ratio of length (for rivers) or area (for lakes). The equation for the final score can be expressed as:

$$RHI = \frac{\sum_{i=1}^{R_s} (RHI_i \times A_i)}{\sum_{i=1}^{R_s} A_i} \quad (2)$$

where RHI = the final score of a river (lake), A_i = the length (area) of the i th river (lake) section, and R_s = the amount of the total sections. Based on the final score, a certain river or lake can be categorized as “very healthy” ($RHI \geq 90$), “healthy” ($75 \leq RHI < 90$), “subhealthy” ($60 \leq RHI < 75$), “unhealthy” ($40 \leq RHI < 60$), or “hazardous” ($RHI < 40$).

5.4. Limitation and Future Development

It should be mentioned that the main limitation of the new framework is the over-simplification of some indicators (e.g., eco-water/environmental flow) for the convenience of implementing the RCS by non-experts. Furthermore, those more sophisticated indicators (e.g., ecological processes and ecosystem resilience) excluded from the framework should not be ignored by researchers, as they can better reflect the freshwater health as a dynamic status with multiple interrelated constituents.

Adopting a simplified framework does not imply that the scientific principles are compromised; on the contrary, ongoing research should be carried out to monitor the efficacy of the framework and make adjustments accordingly.

Although the RCS has been proved as an effective system to manage freshwater resources and improve the health status, challenges still exist due to the fast urbanization in China and the increasing pollutant emission and water consumption, which may significantly influence people's lives. The future development of the RCS should be based on the essential goal that freshwater health status meets people's expectation for an enjoyable living environment, which is obviously more fundamental than any "index" or "grade" that describe the condition of water bodies in an unintuitive way. Some pilot works [73] have been done to explore a method to quantify the sensory aspect of rivers and lakes. In 2019, the Ministry of Water Resources in China had also set the objective of the RCS as "unblocked rivers, clear waters, green banks, beautiful scenery, people in harmony". Priority will be given to a few cities, regions, and catchments of significance to build healthy freshwater ecosystems that meet ecological, sensory, and safety demands under the framework of the RCS; those examples can further be the role models for the rest of China.

Table 6. The proposed new indicator framework. The weights for categories and sub-categories are shown in parentheses.

Category	Sub-Category	Indicator	Selection	More Description	Data Source	
Ecosystem integrity (0.7)	Physical habitat (0.2)	Water connectivity	Optional	Instream obstructions (rivers) and incoming discharge (lakes)	Engineering record; field investigation; remote sensing	
		Riparian naturalness	Mandatory	Bank stability and vegetation coverage		
		Riparian wideness ^R	Optional	Width during the dry season	Field investigation; remote sensing	
		Lake shrinking ratio ^L	Mandatory	Compared with the area in the 1950s		
	Water quantity (0.15)	Eco-water satisfaction	Mandatory	Follow SL/Z 712-2014	Hydrologic monitoring live data; on-site monitoring; the historical records	
		Water quantity mutation	Optional	Use monthly surface discharge deviation for rivers Use monthly incoming discharge deviation for lakes		
	Water quality (0.15)	Water quality	Mandatory	Follow GB3838-2002 and SL395-2007 [46,47]		Local water quality reports; live data or on-site monitoring
		Substrate contamination	Optional	Follow GB15168-2018 [48]		
		Eutrophication ^L	Mandatory	Follow SL395-2007 [47]		
	Aquatic life (0.2)	Macroinvertebrate *	Optional	Use the Benthic Index of Biological Integrity (B-IBI) [74,75]	Field investigation by specialists	
		Fish	Mandatory	Compared with the status before 1980	Data from aquaculture departments; field investigation by specialists	
			Optional	Population, diversity and the existence of rare birds	Data from forestry departments or environment protection agencies; field investigation by specialists	
		Plankton density ^L	Mandatory	Compared with the status before 1980	Field investigation by specialists	
		Macrophytes	Optional	Compared with the status of specific periods in history	Field investigation; remote sensing	
		Flood protection	Optional	Length of the embankment and other engineering interventions	Data from water conservancy departments	
Non-ecological performance (0.3)	Social services (0.2)	Water supply	Optional	How often the daily averaged discharge (or water level) is higher than the threshold for abstraction	Reports of local water authorities	
		Land development	Optional	The ratio of developed riparian land to the reference value	Data from local planning consents	
		Navigation ^R	Optional	The ratio of navigable days in a year	Open hydrologic data or official reports	
	Public satisfaction	Mandatory	Public opinion about sensory/recreational aspects, the general condition of physical habitats and the surrounding environment	On-site or online questionnaires		
	Water governance (0.1)	Drinking water zones **	Optional	The ratio of drinking water zones with the required water quality.	Local water quality reports; live data or on-site monitoring	
		Illegal activities (“four chaos”)	Mandatory	Illegal mining, occupation, disposing, and construction are managed.	Reports of local administration	
		Sewage regulation	Mandatory	The outfalls should be registered and well managed with reasonable layouts that do not influence drinking water sources		

^R Applicable to rivers; ^L Applicable to lakes;. * Macroinvertebrate status is assessed using the B-IBI method proposed by [74,75]. ** The concept of water functions zones is simplified to focus on drinking water zones and avoid ambiguity.

6. Summary and Conclusions

In this paper, we analyze the administrative and scientific aspects of evaluating freshwater health in China under the framework of the River Chief System (RCS) and compare those features with the best practices around the world. The most significant distinctions between the principles in China and those overseas are discussed particularly. A new indicator framework is proposed together with a well-structured protocol for implementation. The research findings in the present study will be integrated into China's new national freshwater evaluation standard to be issued this year.

Regarding the administrative aspect, the unique institutional context in China (centralized authority, party-state hierarchy, and cadre responsibility system) make it is essential to adopt the top-down mechanism of accountability to avoid the inaction of local officials in different levels. Thus, the performance of the RCS should be graded in a concise and quantitative way to simplify the workload of local Chiefs who are usually non-experts. Regarding the scientific aspect, social services and water governance indicators should be appropriately integrated into the new framework, as those indicators emphasize some attributes that are particularly valued in China and also sometimes ignored in western counties. Those attributes, for example, include the effectiveness of water resources management by using a centralized model and the harmony between individuals, the society and the environment.

From this study, we argue that a series of issues should be paid attention to when establishing a widely implemented freshwater health evaluation framework, including well-defined objectives and motivations, comprehensive and practical indicators metrics, standardized data acquisition and analysis protocols, and the adaptability for future development. Regarding the last issue, the new framework proposed in this study is expected to be revised for every two years to ensure its appropriateness.

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