

RESEARCH ARTICLE

The future of global river health monitoring

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Abstract

Rivers are the arteries of human civilisation and culture, providing essential goods and services that underpin water and food security, socio-economic development and climate resilience. They also support an extraordinary diversity of biological life. Human appropriation of land and water together with changes in climate have jointly driven rapid declines in river health and biodiversity worldwide, stimulating calls for an Emergency Recovery Plan for freshwater ecosystems. Yet freshwater ecosystems like rivers have been consistently under-represented within global agreements such as the UN Sustainable Development Goals and the UN Convention on Biological Diversity. Even where such agreements acknowledge that river health is important, implementation is hampered by inadequate global-scale indicators and a lack of coherent monitoring efforts. Consequently, there is no reliable basis for tracking global trends in river health, assessing the impacts of international agreements on river ecosystems and guiding global investments in river management to priority issues or regions. We reviewed national and regional approaches for river health monitoring to develop a comprehensive set of scalable indicators that can support “top-down” global surveillance while also facilitating standardised “bottom-up” local monitoring efforts. We evaluate readiness of these indicators for implementation at a global scale, based on their current status and emerging improvements in underlying data sources and methodologies. We chart a road map that identifies data and technical priorities and opportunities to advance global river health monitoring such that an adequate monitoring framework could be in place and implemented by 2030, with the potential for substantial enhancement by 2050. Lastly, we present recommendations for coordinated action and investment by policy makers, research funders and scientists to develop and implement the framework to support conservation and restoration of river health globally.

Introduction

Nearly all aspects of human society are impacted by the health of rivers. Flowing waters act as centres of organisation within the landscape, offering countless cultural and ecological

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services, and supporting a rich diversity of plants and animals. However, rapid changes in water and land use, climate change and a host of other anthropogenic stressors threaten the biodiversity and ecological integrity of these ecosystems [1]. As long ago as 2005, the global Millennium Ecosystems Assessment [2] concluded that freshwater ecosystems were among the most degraded and being used unsustainably. Despite the prominence and persistence of challenges including water security and impacts of climate change on hydrology, attention to the conservation of freshwater ecosystems—including rivers—has nonetheless lagged at the global scale [3]. This may be due to the perception of freshwater systems as a resource for human use rather than a precious habitat [4], their more limited spatial extent that reduces public awareness [5], a historical lack of conservation champions [6], and inadequate transdisciplinary scholarship [7]. Additional hurdles are associated with understanding and managing rivers as complex networks [8], and longstanding traditions of large-scale regulation (i.e., dams, diversions) and water extraction. In response, recent years have witnessed mounting calls for global-scale research and policy actions to stem further losses and degradation of freshwater habitats [9–11].

A significant hurdle to addressing the freshwater biodiversity crisis is that the major global initiatives working to thrust ecosystems onto the global development agenda consistently lack robust representation of freshwater health. These initiatives include The Economics of Ecosystems and Biodiversity (TEEB) for water and wetlands [12], the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Agenda 2030 on Sustainable Development (the SDGs), the post-2020 Kunming-Montreal global biodiversity framework (GBF) and the UN Decade on Ecosystem Restoration. All of these, together with globally impactful periodic reports such as the Ecological Footprint indicator [13], the Planetary Boundaries framework [14], the Water Footprint indicator [15], and others, lack comprehensive indicators of freshwater ecosystem health. Instead, these efforts generally rely on single or small numbers of proxies. For these reasons, the Emergency Recovery Plan for Freshwater Biodiversity [9], and subsequently the Sustainable Freshwater Transition set out by the UN Convention on Biological Diversity, called for the development of a more robust and inclusive suite of freshwater biodiversity and ecosystem health indicators. The aim of such indicators would be to provide a foundation for consistent, widespread monitoring as part of international environmental and sustainability agreements, whether focused on fresh waters generally or river health specifically.

This paper seeks to chart a path toward policy-relevant, global river health monitoring. Our approach synthesises and builds on the substantial work to monitor river health at national and regional scales over recent decades. Leveraging knowledge established through mature large-scale programs, we identify a robust framework of indicators that can be refined and improved over time through coordinated global policy, research, and data infrastructure developments (i.e., top-down efforts). This common framework can also support local, national, and regional efforts to monitor river health with protocols that are flexible but sufficiently standardised for results to be compared between contexts (i.e., bottom-up efforts). Our objective is to align diverse monitoring and research efforts toward strategic actions over the next two decades that will ultimately facilitate robust, comprehensive, and feasible reporting on global trends in river health.

Status of large-scale river health monitoring

The first step toward a global river health framework is to evaluate current policies, concepts, and data for monitoring and assessment of river health at large-scales (i.e., national to global). The most important development in the last century is undoubtedly the passage of national—

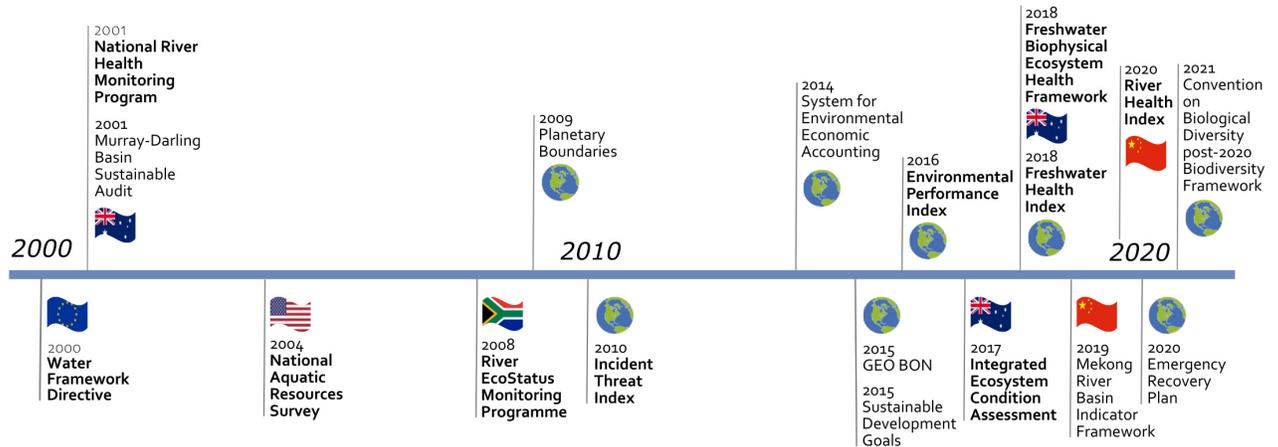


Fig 1. Timeline of national or regional and global frameworks used to evaluate river health. Years indicate the point at which the framework was initially published as peer-reviewed or grey literature; the subset of programs or approaches analysed herein are bolded.

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or, in the case of the European Union, regional—laws and regulations that mandate restoration and maintenance of freshwater ecosystems to meet water quality or condition standards. Examples of such laws, most of which have been enacted in the last 50 years include the Clean Water Act (1972) in the USA, the Resource Management Act (1991) in New Zealand, the European Water Framework Directive (2000), the CONAMA—Conselho Nacional do Meio Ambiente 357/2005 in Brazil (2005) and the Water Act of South Africa (1998). These laws created legal and financial incentives within nations to develop and refine consistent monitoring and assessment methods over time (Fig 1), including indicators and metrics to evaluate the status of river ecosystems [16, 17]. Although mature, large-scale programs are mostly restricted to a handful of economically advantaged nations, they offer a critical foundation for international or intercontinental knowledge transfers to support monitoring of river health globally [18].

The design of any monitoring program begins with the definition of ecosystem health. In this paper, we define ecosystem health as 'The ability of the aquatic ecosystem to support and maintain key ecological processes and a community of organisms with a species composition, diversity, and functional organisation as comparable as possible to that of undisturbed habitats within the region' (Schofield & Davies, 1996 after Karr & Dudley, 1981). Assessments of river health can emphasise different types of indicators, which are often classified as driving forces, pressures, state, impact, and response (i.e., the DPSIR framework; [19]). Our definition of river health sets the stage for selecting indicators that reflect biophysical conditions, thus focusing on ecosystem state. This focus represents a strong departure from previous or ongoing evaluations of river health at global scales. Global assessments to date have instead concentrated on pressures on aquatic ecosystems, largely because of the relative ease of computing changes—actual or projected—in land use, anthropogenic impacts, and climate—based on remote sensing and modelled data. These pressure-based models have yielded estimates of water security and risk of biodiversity loss [20], human use of ecosystem services [21], and temporal and geographic changes in biodiversity [22].

The challenges, however, with such models are that pressures on aquatic ecosystems may or may not reflect ecosystem condition or state [23, 24], and therefore can offer only limited insight into their relationship with driving forces and responses that can be adjusted through management, mitigation, or restoration [25]. Weak or unverifiable linkages between

ecosystem state, pressures, and driving forces are unlikely to offer the strong justification needed to support policy changes or investments in river health [17, 25]. Our focus on ecological state excludes human valuations of rivers, which may encompass socioeconomic, cultural, or spiritual values [26]. Although such valuations can and have been included in large-scale assessments of river health (e.g., [27]), we advance that the first priority is to address the considerable knowledge gaps and technical barriers to evaluating the biophysical state of rivers at a global scale. Our position is that there is an urgent need to develop a framework around ecosystem state, and forward the corresponding scientific and research agenda. Such a framework can then provide the foundation to subsequently incorporate relationships with responses and driving forces, as well as holistic social and human values.

The final critical component in designing a river health framework is the availability and quality of data to capture the chosen indicators. Data sources can be grouped into three, not necessarily mutually exclusive, classes: *in situ* monitoring data (including conventional biological sampling and *in situ* sensors as well as novel approaches of uncrewed vehicles, crowdsourcing, or the analysis of environmental DNA), remote sensing imagery (including prospective satellite missions), and modelling (including predictive hydrological models, statistical models, or artificial intelligence and machine learning approaches). While data sources are generally expanding, fundamental challenges persist. The data required for multi-indicator monitoring frameworks are collected by myriad entities, many of which may not openly share data; datasets may also be scale-dependent, discontinuous, or come in incompatible formats (e.g. raster, vector, tables). A forward-thinking river health framework should, therefore, consider both current and anticipated data developments.

The quality of data available at varying scales is a foundational challenge. Bottom-up approaches to assess river health rely on collecting and compiling local information, often with high precision *in situ* data; yet this makes the expansion to larger regions time-consuming or even practically impossible. Indeed, given the paucity of river health monitoring in many parts of the world [18], monitoring global river health based on compilation of local information is a formidable task. However, top-down approaches, which usually rely on remote sensing or modelling, tend to use limited amounts of input data and are often coarse in their spatial or temporal resolution, rendering local interpretations inaccurate and uncertain.

To blend both bottom-up and top-down approaches in a global framework requires a scalable geospatial method that can discern local hydrographic features at high spatial resolution, while also allowing linkages to coarser global datasets or modelling results. A standardised, common geospatial framework based on pre-defined spatial units (e.g., river reaches and their catchments) can leverage the strengths of both approaches and adaptively incorporate higher-quality data over time. For example, results from top-down analyses can serve as initial placeholders until more precise local information (e.g., from national or regional monitoring programs) becomes available. These types of multi-scale hydrographic frameworks are increasingly available at full global coverage and high spatial resolution (e.g., HydroATLAS [28] MERIT Hydro-Vector [29]).

Besides scalability, a second foundational challenge in monitoring river health is the inherent topological structure of fluvial systems. In contrast to terrestrial systems, river health is determined by conditions in upstream drainage areas as well as more proximate influences. Point-based biological monitoring or instream water quality data can provide an integrated perspective (i.e., a healthy local habitat may indicate good conditions across the entire upstream catchment), and novel approaches such as eDNA analyses and improved chemical detectors offer promising avenues to scale up *in situ* sampling in the future [30]. But these methods are not yet available at a global scale, and may continue to require modelling support (e.g., for chemical compounds that are difficult to detect in the field) [1]. Using top-down

approaches, upstream influences can be integrated through data processing and modelling that nests information within hierarchical catchments and allows routing of physical or biological properties along river networks (e.g., using accumulation and decay functions) (e.g., [24]). Of particular importance is the ability to evaluate longitudinal, lateral, vertical, and temporal connectivity, which is vital to freshwater ecosystems as it defines the fluxes, movement or dispersal of species, materials (including water and sediments), nutrients, and energy [31]. For this reason, a recommended framework should include a versatile geospatial data concept that can incorporate topological information of upstream, downstream and lateral connections as well as nested and hierarchical relationships between hydrographic features.

Methods

Review of monitoring approaches

We initiated this work by comprehensively reviewing existing programs and approaches to monitor and assess river health around the world [32]. We restricted our review to those implemented at a national, regional, or global scale, as we considered these most likely to possess the properties necessary to inform a global monitoring framework. We focused on operational programs that were developed for monitoring (i.e., surveillance) of river health, rather than investigative approaches. In addition to these, we also evaluated existing global indices of river health; although differing greatly from monitoring programs, their design and implementation offer important insights into the current state of global river health monitoring.

We compared each approach against the following seven criteria that are considered integral to a successful framework: consistency, representativeness, robustness, flexibility, scalability, feasibility, and informativeness [33]. To assess **consistency**, **representativeness**, and **robustness**, we evaluated methods of data collection and the number and types of indicators used. **Flexibility**, **scalability**, and **feasibility** were explored qualitatively, primarily based on the indicators and methods of data collection, followed by the complexity of methods used to harmonise and integrate data. Lastly, **informativeness** was qualitatively assessed in the conceptual design and methods that were used to frame and report results.

From this initial review, we identified 10 programs or approaches that met the majority of the seven criteria (Fig 1). From each, we summarised the features or attributes that have the greatest potential to inform the design of a global framework: the indicators used in the assessment, the biophysical components that the indicators reflect, data types, methods of data harmonisation and integration, and practical insights applicable to the design of a global monitoring framework.

Development of the global monitoring framework

Based on the above review, we develop a framework of indicators for global river health monitoring, which we evaluated for feasibility of implementation at two time periods: by 2030 and by 2050. Rather than including indicators based on current feasibility, we considered all potential indicators, regardless of the state of readiness of the data sources or prognosis for development, even by 2050. For example, careful research and expert knowledge have gone into identifying Essential Biodiversity Variables [34, 35], a suite of variables that are broadly agreed as necessary and sufficient to monitor national to global biodiversity. However, much coordinated and systematic development of data sources is still needed to characterise these variables at global scales [36]. Building on these and other studies that have evaluated and identified “ideal” indicators allows us to diagnose research and data gaps that, if addressed, could substantially advance monitoring of global river health. The 2030 and 2050 time horizons were chosen in light of technical considerations as well as the anticipated updating of global

sustainability and ecological health initiatives (e.g., the SDGs which expire, but may be refreshed, in 2030). Given the time frames required for research and operationalizing new data sources and methods, the 2030 framework represents data sources and methods that are effectively available in the near term. The second time period of 2050 allows us to evaluate the technical horizon for promising yet feasible technologies, methods or infrastructure that can advance the accuracy and informativeness of these indicators in the near-to-medium future.

Results

Review of monitoring approaches

Because existing major river health monitoring programs stem from national or regional legislation, they vary in purpose (i.e., matched to specific regulatory context) and are influenced by the approaches and technologies in use at the time of their development (Fig 1; Table 1).

Nearly two decades separate early, well-established frameworks [i.e., National Aquatic Resources Survey (NARS) and Water Framework Directive (WFD)] from later ones whose implementation is less well-documented [i.e., Freshwater Biophysical Ecosystem Health Framework (FBEHF) and River Health Index (RHI)]. More recent frameworks tend to include variables based on remote-sensing data, and more explicitly incorporate scale and catchment hierarchy into the conceptual designs and reporting of results [32]. Each of the large-scale river health programs has perceived advantages and disadvantages (Table 1), and collectively they exemplify the key attributes a large-scale framework should possess. These include: a clear definition of ecosystem health; indicators of multiple biophysical components; standardised methods and protocols of data collection and integration; and scale independence (Table 1). The main reasons for differences in the choice and treatment of components originate from the definition of “freshwater health”, which underlies the conceptual design that combines driving forces, pressures, state, impact and responses. For example, New Zealand’s FBEHF defines ecological integrity as the maintenance of structure and function “in the face of external stress”. Therefore, while the FBEHF relies on biophysical indicators to assess condition (i.e., state), it also recommends conceptual modelling of stressor pathways (i.e., pressures and driving forces) to guide management and policy actions for remediating indicators that are below targets [33].

The biophysical categories (hereafter, ‘components’) that are monitored, and the range and type of associated indicators differ greatly among river health monitoring frameworks. The four most commonly included components are 1) biology (aquatic life), 2) water quality (physicochemical conditions), 3) physical habitat, and 4) hydrology (water quantity & dynamics) (Table 1), suggesting broad agreement that these components constitute a robust and comprehensive basis for river health monitoring. A majority of the national and regional programs concur in relying on the state of the biological indicators as the primary reflection of aquatic ecosystem or river health; greater differences occur in the treatment of abiotic indicators. Abiotic features may be considered primarily with respect to influencing the biological responses (e.g., NARS, National River Health Program) or incorporated as part of the definition and measurement of ecological health (e.g., WFD, RHI, FBEHF).

Limitations associated with the scale of the monitoring also drive some design decisions, such as availability of data that can reflect indicators of ecosystem health at large scales. This can be seen most starkly in the strong contrast between regional or national-scale monitoring programs and existing global frameworks. Global frameworks tend to emphasise pressures rather than ecosystem state (Table 1) [32], reflecting current data constraints to assess river health at large scales. Regardless of the source and types of data that inform indicators, frameworks share similarities in the methods used to translate indicator data into an assessment of

Table 1. Large-scale programs and approaches used to inform a global monitoring framework. Description and attributes of selected large-scale (i.e., national and regional) monitoring programs or global assessment methods determined as meeting a majority of seven criteria for a successful framework [33]. In any monitoring program, a conceptual framework designates relationships between Indicators, which are often grouped by broader biophysical Components (i.e., themes or categories). Further, the conceptual framework of a specific program may treat Components as driving forces (D), pressures (P), state (S), impact (I), or responses (R) (i.e., the DPSIR framework). [Note: Components and Indicators are presented using the terminology of the individual frameworks]. A majority of frameworks include procedures where indicator data are harmonised (i.e., standardised), integrated (i.e., combined) into Component scores, and assigned to condition classes for reporting the condition of the ecosystem.

| Monitoring Program | Biophysical Components‡ (DPSIR category) | Indicators | Data Type | Data Methods | | | Lessons for global monitoring framework |
|---|---|--|--|--|--|--|--|
| | | | | Harmonisation | Integration | Reporting | |
| Freshwater Biophysical Ecosystem Health Framework (FBEHF), New Zealand [33] | Aquatic Life (S) Physical Habitat (S) Water Quality (S) Water Quantity (S) Ecological Processes (S) | Waterbirds, native fish, invertebrates, macrophytes, periphyton, microbes, oxygen, temperature, pH, sediment, nutrients, toxicants, water extent, hydrologic variability, connectivity, substrate, physical habitat extent/form, habitat connectivity, riparian, biotic interactions, biogeochemical processes | <i>in situ</i> (100%) | Indicator data are scaled 0–1 based on modelled or measured reference values | Expert weighted averaging | Indicator and component scores are assigned to condition classes; four (recommended) classes are ‘excellent’ to ‘poor’ | Clear definition of ecological integrity Essential indicators and key performance attributes are defined Flexible integration |
| National Aquatic Resource Surveys (NARS), USA [37] | Biological (S) Chemical (S) Physical (S) | Periphyton, benthic macroinvertebrates, fish, phosphorus, nitrogen, salinity, acidification, sediment, instream fish habitat, riparian vegetative cover, riparian disturbance, faecal indicators, mercury in fish tissue, algal toxins | <i>in situ</i> (100%) | Indicator data are scaled based on the distribution of values across regionally identified reference sites | Not applicable (indicator scores are not integrated) | Indicator scores are assigned to three condition classes from ‘good’ to ‘poor’ Health-related indicators are above/below fixed benchmarks | Clear definition of ecological integrity Standardised data collection and integration protocols Sampling design is rigid and expensive |
| River EcoStatus Monitoring Programme (REMP), South Africa [38, 39] | Biology (S) Physical Habitat (S) Hydrology (D) Geomorphology (D) Physico-chemistry (D) | Fish, invertebrates, instream habitat, riparian habitat, riparian vegetation, discharge, substrate, submerged vegetation, anthropogenic disturbance, water odour/clarity/colour, algal growth | <i>in situ</i> , Modelling | Indicator data are scaled based on reference values using rule-based modelling, determined by expert ratings | Expert weighted averaging | Composite score is assigned to six condition classes from ‘natural’ to ‘critically modified’ | Driver-response model facilitates interpretation of changes Tiered approach allows refinement as data gaps are filled |
| The River Health Index (RHI), China [40]‡ | Aquatic Life (S) Physical Habitat (S) Water Quality (S) Water Quantity (S) | Fish, macroinvertebrates, waterbirds, plankton, macrophytes, riparian naturalness/wideness, dissolved oxygen, pH, nitrogen, phosphorus, heavy metals, flow connectivity, hydrologic modification | <i>in situ</i> , Remote sensing, Modelling | Indicator data are scaled 0–100 based on site-specific reference values | Expert weighted averaging | Composite score is assigned to five condition classes from ‘very Healthy’ to ‘hazardous’ | Essential indicators outlined Standardised data collection and integration protocols |

(Continued)

Table 1. (Continued)

| Monitoring Program | Biophysical Components‡ (DPSIR category) | Indicators | Data Type | Data Methods | | | Lessons for global monitoring framework |
|---|---|---|--|---|---|--|---|
| | | | | Harmonisation | Integration | Reporting | |
| Water Framework Directive (WFD), Europe [41] | Biological Quality Elements (S) Hydro-morphological Quality Elements (S) Chemical & Physico-chemical Quality Elements (S) | Aquatic flora, benthic macroinvertebrates, fish, water flow, connection to groundwater, river continuity, river form (depth, width, bed structure), substrate, riparian structure, temperature, oxygen, salinity, acidification, nutrients, priority substances*, other substances* | <i>in situ</i> (100%) | Indicator data are scaled 0–1 based on measured or modelled reference values by region and ecosystem type | ‘One-out-all-out’ (i.e., lowest class across components represents the overall ecological status) | Component scores are assigned to five condition classes from ‘high’ to ‘bad’ | Essential indicators outlined Standardised data collection and integration protocols |
| Integrated Ecosystem Condition Assessment (IECA) Framework, Australia [42]‡ | Hydrology (S) Water Quality (S) Structural integrity (S) Aquatic ecosystem connectivity (S) Biodiversity (S) | Specific indicators are not prescribed; framework outlines criteria and potential indicators for each component, as well as stressors | <i>in situ</i> , Modelling | Indicator data are scaled 0–100 based on “baseline” conditions (current condition, Ramsar “at the time of listing”, pre-European, a predetermined time) | Simple or expert-based weighted averaging | Component scores are assigned to five condition classes from ‘largely unmodified’ to ‘severely modified’ | Designed for application at various scales Compatibility with other regional frameworks Flexibility to select appropriate indicators |
| National River Health Monitoring Program (NRHP), Australia [43] | Biological (S) Physical Habitat (D) | Macroinvertebrates, physical morphology and bedform, substrate, planform channel features, floodplain characteristics, bank characteristics, instream vegetation/ organic matter, physical condition/habitat assessment, riparian vegetation, site observations | <i>in situ</i> , Modelling | Indicator data are scaled based on reference values modelled from least-disturbed sites | Not applicable (single ecosystem state indicator) | Indicator scores are assigned to five condition classes from ‘more diverse than reference’ to ‘extremely impaired’ | Reliance on a single indicator of ecosystem state limits ability to use or interpret results Inappropriate or inconsistent reference site selection can bias results |
| Freshwater Health Index (FHI) [27]‡ | Ecosystem Vitality (I) | Deviation from natural flow, groundwater depletion, suspended solids, nitrogen, phosphorus, water quality indicators of major concern, bank modification, flow connectivity, land cover naturalness, changes in species of concern and invasive species (#, pop size) | <i>in situ</i> , Remote sensing, Modelling | Indicator data are scaled 0–100 based on indicator-specific reference values (modelled or set thresholds) | Expert weighted averaging | Single component scores (0–100) are reported in addition to indicator scores | Adaptability to existing datasets Score calculation accommodates missing data |

(Continued)

Table 1. (Continued)

| Monitoring Program | Biophysical Components [‡] (DPSIR category) | Indicators | Data Type | Data Methods | | | Lessons for global monitoring framework |
|---|--|---|--|--|--|--|--|
| | | | | Harmonisation | Integration | Reporting | |
| Incident Threat Indices (ITI) to Human Water Security and River Biodiversity [20] | Catchment Disturbance (P) Pollution (P) Water resource development (P) Biotic factors (P) | Cropland, impervious surface, livestock, wetland dysconnectivity, soil salinization, nitrogen/ phosphorus/ mercury/ pesticide/sediment/ organic loading, potential acidification, thermal alteration, dam density, river fragmentation, consumptive water loss, human water stress, agricultural water stress, flow disruption, non-native fishes (% and #), fishing pressure, aquaculture pressure | Remote sensing (100%) | Indicator data are scaled 0–1 based on distribution of values across all grid cells globally | Expert weighted averaging applied to indicators and components | Maps of scaled indicator scores and composite (i.e., incident threat) scores | Information is currently considered insufficient for a similarly meaningful adjusted index for biodiversity |
| 2016 Environmental Performance Index (EPI) [44] [‡] | Water Resources (P) Agriculture (P) Forests (P) Fisheries (S) Biodiversity & Habitat (S) Climate & Energy (P) | Wastewater treatment, nitrogen use efficiency/ balance, tree cover loss, fish stocks, marine protected areas, terrestrial biome and species protection (national and global), carbon intensity trends | <i>in situ</i> , Remote sensing, Modelling | Indicator data are scaled 0–100 based on distribution of values or set thresholds (e.g., international treaties, scientific) | Weighted averaging is applied to create scores for issues and objectives | Countries are ranked on component scores | Broad-scope dashboard indicator Use of readily available data Room to include indicators that more closely reflect aspects of river health |

[‡]Only biophysical components measured in frameworks are reflected (i.e., components that measured social values or governance structures are not included)

*WFD Annex; determined and updated through periodic review process

[33] Clapcott et al., 2018; [37] US EPA 2020; [38, 39] Dallas et al. 2008, Kleyhans et al. 2008; [40] Xie et al., 2020; [41] Europai and Tanasca 2000; [42] Department of the Environment and Energy (2017); [43] Turak et al. 2006; [27] Vollmer et al., 2018; [20] Vörösmarty et al., 2010; [44] Hsu et al., 2016

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ecological condition. Large-scale frameworks consistently entail harmonisation (i.e., standardisation) of indicator data to a common scale (e.g., 0–100) against benchmark conditions; these may be relative to local, regional, or environmentally similar reference sites, based on the distribution of values, or predetermined targets. It is typical for assessments to integrate harmonised indicator scores to the level of components and/or to an overall score (though exceptions exist, e.g. NARS). Methods of integration range from simple or geometric averaging to expert ratings. Lastly, for reporting assessment results, integrated scores are commonly classified into 3–6 condition categories (e.g., NARS, RHI, WFD) or a condition gradient (e.g., River EcoStatus Monitoring Programme), although reporting may also include fixed thresholds (e.g., NARS) or proximity to goals (e.g., Environmental Performance Index).

Development of the global framework

Across the four biophysical components, we identified a comprehensive but parsimonious suite of indicators of river health, and provide a prognosis of their readiness at a global scale in 2030 and 2050 (Table 2; S1 Table). Since these indicators were selected to represent ecosystem state rather than driving forces, pressures, impacts, or responses, all data sources must ultimately be based on either direct measurements or estimation of biological, water quality,

Table 2. Proposed framework of indicators to monitor global river health. Each indicator is described with both challenges and opportunities for application to global monitoring, the methods available for implementation by 2030, and recommendations for development toward more accurate and widespread implementation by 2050 [see S1 Table for sources of *in situ*, remote sensing, and modelled datasets to support development of specific indicators]. Inclusion of each indicator within national or regional and global monitoring programs is shown (● = included, × = not included).

| Component | Indicator | Inclusion in regional or global programs† | | | | | | | | | | Current data challenges and opportunities to advance global monitoring | Recommended Data Sources and Methods | |
|-----------|--------------------------|---|---|---|---|---|---|---|---|---|----|--|--|--|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | 2030 | 2050 |
| Biology | Fish Abundance | ● | ● | ● | ● | ● | × | ● | × | × | × | <ul style="list-style-type: none"> Poorly represented by presence-only data, requires <i>in situ</i> survey or catch data Global compilation of <i>in situ</i> data exist, but is geographically biased and limited eDNA estimates of biomass and abundance likely to remain unfeasible at the global scale | Living Planet Index for riverine fish | Living Planet Index for riverine fish at basin scale with improved taxonomic and geographic representation |
| | Fish Richness | ● | ● | ● | ● | ● | × | ● | × | × | × | <ul style="list-style-type: none"> Global compilations of <i>in situ</i> data exist but are geographically biased and limited Reliance on species distribution modelling may overestimate diversity Untapped sources of <i>in situ</i> data are museum specimens and citizen-science networks eDNA could rapidly increase coverage and temporal resolution of global monitoring | Sampled Red List Index for riverine fish (based on random sample of non-data-deficient freshwater species from globally compiled <i>in situ</i> data) | Sampled Red List Index for riverine fish improved by strategic additions to global <i>in situ</i> datasets from museum specimens, validated citizen-science observation, and eDNA monitoring |
| | Invertebrate Diversity | ● | ● | ● | ● | ● | × | ● | ● | × | × | <ul style="list-style-type: none"> Global compilations of <i>in situ</i> data exist but are geographically biased; incidence data and range maps are limited Biomonitoring focuses on Wadeable streams No internationally accepted standards for invertebrate collection and processing; may be highly variable depending on historical approach, program emphasis, and habitat type eDNA could rapidly increase coverage and temporal resolution of global monitoring | Model of biotic integrity calibrated with existing compiled <i>in situ</i> data | Model of biotic integrity calibrated with newly compiled <i>in situ</i> data including widespread eDNA monitoring |
| | Aquatic invasive species | × | ● | × | ● | ● | ● | × | × | ● | × | <ul style="list-style-type: none"> Global compilation of <i>in situ</i> data exists but are geographically biased and limited Biomonitoring surveys may not consistently differentiate non-native status eDNA and citizen-science networks could rapidly increase coverage and temporal resolution of global monitoring | Model of invasion threat based on land use and development (pressure-based) | Model of aquatic invasive species richness calibrated with <i>in situ</i> observations (state-based) |
| | Primary Productivity | ● | ● | ● | ● | ● | × | ● | × | × | × | <ul style="list-style-type: none"> Global compilation of <i>in situ</i> data for development of models is recent, largely concentrated in North America Limited understanding or information of complex terrestrial and aquatic dynamics that underlie metabolic regimes in rivers Climate change is likely substantially altering metabolic regimes Remote sensing of chlorophyll as a proxy is limited to large, low turbidity river systems | Modelling of riverine primary productivity and ecosystem respiration based on light, thermal and flow regimes, calibrated with geographically biased <i>in situ</i> dissolved oxygen temperature, and PAR data | Modelling of riverine primary productivity and ecosystem respiration calibrated with improved geographic representation |

(Continued)

Table 2. (Continued)

| Component | Indicator | Inclusion in regional or global programs† | | | | | | | | | | Current data challenges and opportunities to advance global monitoring | Recommended Data Sources and Methods | |
|---------------|------------------------|---|---|---|---|---|---|---|---|---|----|--|--|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | 2030 | 2050 |
| Water Quality | Water temperature | • | × | • | • | • | × | × | • | • | × | <ul style="list-style-type: none"> Limited network of <i>in situ</i> gauges Global physical models and remote sensing are limited to large rivers | Physical model calibrated with <i>in situ</i> and remote sensing data | Higher-resolution physical model calibrated with data from more <i>in situ</i> gauges and higher-resolution thermal infrared sensors |
| | Nutrient concentration | • | • | × | • | • | • | • | • | • | × | <ul style="list-style-type: none"> Recent global compilations of <i>in situ</i> data Global models tend to focus on load and yield at catchment scale and export to oceans, not instream concentrations Nitrogen and phosphorus are optically inactive, but remote sensing provides a proxy (e.g. chlorophyll) | Physical model of nutrient loading that incorporates hydrological dynamics | Higher-resolution physical model of nutrient concentration calibrated with <i>in situ</i> data from global database |
| | Suspended sediment | • | • | • | × | × | • | • | • | • | × | <ul style="list-style-type: none"> Remote sensing & modelling of suspended sediments are well developed, but limited to rivers ≥90m wide Model improvement requires geographically dispersed <i>in situ</i> data Only sparse <i>in situ</i> measurements of bedload sediment transport exist | Remotely-sensed surface reflectance model calibrated with limited <i>in situ</i> suspended sediment data for large rivers | Remotely-sensed surface reflectance model with high-resolution data calibrated with widespread <i>in situ</i> suspended and bedload sediment data for all river sizes |
| | Ecotoxicants | • | • | × | • | • | × | × | × | • | × | <ul style="list-style-type: none"> Most ecotoxicants are optically inactive Few water quality datasets include metals or contaminants of emerging concern, including pharmaceuticals and nanoparticles Lack of knowledge of transferability of models from data-rich to data-poor areas (i.e., pollutant sources and concentrations often highly localised, with information on mechanistic linkages missing) | Pressure-based proxy based on wastewater inputs and treatment level, land use (e.g., mining, industry), and fate modelling | Nested basin-scale models based on local mechanistic linkages |

(Continued)

Table 2. (Continued)

| Component | Indicator | Inclusion in regional or global programs† | | | | | | | | | | Current data challenges and opportunities to advance global monitoring | Recommended Data Sources and Methods | |
|------------------|---------------------------|---|---|---|---|---|---|---|---|---|----|---|--|--|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | 2030 | 2050 |
| Physical Habitat | Connectivity | • | × | • | • | • | • | • | • | • | × | <ul style="list-style-type: none"> Global mapping of longitudinal barriers is rapidly improving but remains inconsistent Sparse global datasets on natural longitudinal fragmentation (i.e. waterfalls and other natural physical barriers, drying) Global models of longitudinal fragmentation already exist Limited research on lateral connectivity by remote sensing and means of proxies | Model based only on major longitudinal barriers including coarse proxies for latitudinal, vertical, and temporal connectivity | Model based on most longitudinal & lateral barriers and water presence and dynamics detected with high-resolution remote sensing data |
| | Channel feature diversity | • | • | • | • | × | × | × | • | × | × | <ul style="list-style-type: none"> No large-scale dataset or model currently exist Automated identification of channel form is limited to large rivers due to satellite image resolution and overhanging riparian vegetation Remotely sensed mapping of fluvial wood is not yet possible; still requires <i>in situ</i> survey or point-based identification from high-resolution imagery LiDAR enables high-resolution vegetation-free topographic data but has limited spatial coverage and low temporal resolution | Automated identification of channel planform for large rivers using multispectral imagery | Automated identification of channel planform and feature diversity for all rivers using spaceborne LiDAR |
| | Riparian vegetation | • | • | • | • | • | × | • | • | × | × | <ul style="list-style-type: none"> Remote sensing options for large-scale analysis are limited to monitoring vegetation extent and structure (i.e., excludes species composition, diversity) Models of riparian vegetation condition already exist at large scale (e.g., Europe) but no global dataset or model currently exist Limited spatial coverage and temporal resolution of LiDAR | Remote sensing of vegetation extent and structure using multispectral imagery; bounded to riparian zones by topographic analysis | Remote sensing of vegetation extent, structure, density, and composition using multispectral imagery and spaceborne LiDAR; bounded to riparian zones by topographic analysis |
| | Instream vegetation | • | • | × | • | • | × | • | • | × | × | <ul style="list-style-type: none"> No large-scale dataset or model currently exist Remote sensing options lack the combination of spatial, temporal, spectral and radiometric resolution needed for aquatic plants and macroalgae Remote sensing is limited by overhanging riparian vegetation, patchiness, benthic substrate, and water attenuation <i>In situ</i> data are not routinely or comprehensively collected in monitoring programs | None available | Predictive model of aquatic plant abundance and diversity based on floodplain extent, inundation, and discharge, validated by high-resolution multispectral imagery |

(Continued)

Table 2. (Continued)

| Component | Indicator | Inclusion in regional or global programs [‡] | | | | | | | | | | Current data challenges and opportunities to advance global monitoring | Recommended Data Sources and Methods | |
|-----------|----------------------|---|---|---|---|---|---|---|---|---|----|--|--|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | 2030 | 2050 |
| Hydrology | Surface water extent | • | × | × | • | × | × | • | × | × | × | <ul style="list-style-type: none"> Global mapping of surface water extent, seasonality, and longer-term change exists but is limited to large rivers (30-m resolution pixels) Openly-accessible remote sensing data with spatial resolution <30m for medium rivers are available only since 2014; no openly accessible data for small rivers (<5 m) Mapping of surface water with remote sensing data is an emerging topic, but river monitoring remains limited by trade-offs between spectral and spatial resolution (i.e., mixed pixels), the diversity of optical properties of water, and overhanging vegetation Need to distinguish lotic vs. lentic and natural vs. artificial water bodies | Trained classification of 10-m resolution remote-sensing data (e.g., Sentinel-2) | Model based on trained classification of 3-m resolution remote-sensing data (e.g., Planet Scope) and topographic analysis for vegetated streams and wetlands |
| | Flow alteration | × | × | • | • | • | • | • | × | • | × | <ul style="list-style-type: none"> No globally coordinated network of streamflow gauges exists; global databases exist but are limited by inconsistent data sharing by national gauging networks Streamflow gauges disproportionately monitor large, developed, perennial, regulated rivers Global models estimate natural and altered flow regime but spatial and temporal downscaling of human impact remains a challenge No large-scale remote sensing monitoring existed until recently, but the Surface Water and Ocean Topography (SWOT) altimetry mission (2022 satellite launch) will provide estimates of discharge for all rivers wider than 100 m, and for a subset of those down to 50 m | Global hydrological model calibrated with available <i>in situ</i> gauges and remote sensing data for large to medium rivers | Global hydrological model with improved human impact data; calibrated with discharge data from strategically expanded <i>in situ</i> gauges and citizen-science collected data for small streams, and satellite altimetry for medium-large rivers |

[‡] 1. Freshwater Biophysical Ecosystem Health Framework [33]; 2. National Aquatic Resource Surveys [37]; 3. River EcoStatus Monitoring Programme [38, 39]; 4. The River Health Index [40]; 5. Water Framework Directive [41]; 6. Freshwater Health Index [27]; 7. Integrated Ecosystem Condition Assessment Framework [42]; 8. National River Health Monitoring Program [43]; 9. Incident Threat Indices to Human Water Security and River Biodiversity [20]; 10. Environmental Performance Index [44]

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physical habitat, or hydrologic parameters (S1 Table). The exception is where an explicit decision is made to use proxies as an interim measure, due to data or modelling limitations. Direct measurement may be done via remote sensing or compilation of *in situ* data, while estimation involves modelling—including interpolation and/or fate-based modelling—that is calibrated with direct measurements.

The framework emphasises modelling approaches, which can produce spatially-explicit estimates of all indicators for all rivers. This stems from the fact that both *in situ* and remote sensing datasets have inherent (often differing) limitations in their utility to reflect the health of freshwater ecosystems at large scales. Modelling can incorporate multiple data sources for the calibration of indicators (or, potentially, interim use of pressure-based proxies), can yield predictions for smaller rivers which are often more data-limited, and offers a way to harmonise

indicators into the same hydrographic structure and scale. Importantly, modelling allows representation of uncertainty, which can be reduced as better or more data are incorporated over time and also indicate priorities for improvement (e.g., by highlighting geographic disparities in *in situ* data).

We organise our presentation of the state-of-the-art methods for river health monitoring by biophysical component, first evaluating indicators based on their current feasibility for implementation at a global scale (i.e., 2030) followed by recommendations for development over the next two decades (i.e., 2050).

Biology

We recommend five biological indicators of river health, which are fish abundance, fish diversity, invertebrate diversity, aquatic invasive species, and primary productivity. Because biological indicators integrate catchment conditions and anthropogenic influences, they are typically considered to best reflect the ecological state and health of riverine (and other aquatic) ecosystems [18]; it is not surprising that they are well represented in biological monitoring programs, even at large scales. However, the state of current data sources demonstrates consistent bottlenecks and limitations to implementation at global scales, which will require considerable investment and focus to overcome. For example, the IUCN Red List and the Living Planet Index, arguably the most developed and recognised global systems to assess conservation status of species, suffer from well-documented taxonomic and geographic bias [45–47].

The most obvious challenge for global monitoring of biological indicators is that remote sensing data offer little utility; the possible exception to this is primary productivity, for which chlorophyll can be used as a (limited) proxy [48]. Capacity to measure or model biological indicators is therefore dictated by the status and availability of global *in situ* datasets, which currently suffer from strong geographic limitations and bias (S1 Table). Given that widespread development of new large scale (i.e., regional or national) monitoring programs is not expected [18], developing untapped sources of *in situ* biological data are essential. The rapid development of eDNA in recent years offers particular promise to help overcome the lack of biological data, but will require investment toward application for specific indicators [49] and implementation at large-scales [50]. For example, although eDNA analyses of aquatic diversity is improving with community approaches such as universal markers or meta-barcoding—and with comparable or greater sensitivity than traditional methods [51]—considerable effort is yet needed to build reference sequences and the genetic databases that these approaches rely on [52]. For these reasons, the potential for other mechanisms to bolster global datasets of aquatic diversity should not be ignored, including processing of museum specimens [53], fostering citizen science observation networks and platforms [54], and collating data from national biomonitoring programs [24]. These options also require little technology, which may be of particular importance for broadening representation in geographically remote areas [55, 56]. Model-based data integration methods also provide ways to leverage this growing quantity and types of biological data being collected [57].

Even anticipated development and expansion of *in situ* data from the above sources will likely contribute little to the improvement of two indicators, which are fish abundance and primary productivity. A primary drawback of eDNA metabarcoding to evaluate biodiversity is limited ability to infer abundance [58]. Citizen-science projects equally emphasise reporting species presence rather than abundance [56]. As such, the dominant sources of *in situ* data for these two indicators are most likely to come from ongoing compilation of data from disparate research and monitoring efforts, the most informative of which include multi-year time series for detection of trends [59, 60]. However, it is not possible to recommend or rely on

contributions by local or even national researchers and networks without acknowledging systemic and well-documented barriers to data sharing, ranging from lack of financial support for data synthesis to cultural perspectives [61]. Given the importance of *in situ* data to inform biological indicators for rivers (and other aquatic ecosystems), we recommend that research funders support the creation and expansion of large-scale datasets [62], as well as adopting data sharing criteria to promote behavioural and cultural shifts in scientific practice [63].

Water quality

Four water quality indicators are recommended to reflect ecological health of rivers: water temperature, nutrient concentrations, suspended sediments, and ecotoxins (Table 2). Despite current shortcomings, we find that several of these indicators are in a favourable position for implementation at a global scale in the near future. We attribute this readiness to the fact that the respective water quality constituents (temperature, nutrients, sediments) are closely tied to physical landscape features and catchment processes that can be modelled, and that are also more readily measured using remote sensing or *in situ* methods. Indicators of water quality are commonly included in large-scale monitoring programs (Table 2), and compilation of *in situ* data that can support improvements in modelling is—albeit in early stages—underway in many places (S1 Table). Indeed, the priority opportunities for improvement that we foresee and recommend are in broadening the collection and global compilation of *in situ* data, including through citizen science monitoring [64], for improved calibration of existing physical models [65, 66]. While satellite-based remote sensing of suspended sediments is already well-developed [67, 68] and will continue to progress thanks to the increasing resolution of satellite-based optical imagery, the resolution of thermal infrared imagery is still relatively coarse (≥ 100 -m pixel size) and can thus be applied to estimate temperature for only very large rivers at present. Nonetheless, higher resolution data afforded by the imminent launch of new sensors is expected to extend thermal remote sensing to smaller rivers and substantially improve the accuracy of global water temperature models [69].

Of the four recommended water quality indicators, ecotoxins are currently the least feasible indicator for implementation in global river health monitoring. This is due to the fact that ecotoxins are optically inactive and highly variable and localised in their release, concentrations and behaviour [70, 71]. The diversity and sources of organic and synthetic chemicals that may be present in fresh waters is daunting. Although agricultural pesticides are often the dominant sources of chemical risk in freshwaters [72, 73], other sources may range from heavy metal effluents from mining operations and urban land uses to endocrine-disrupting pharmaceuticals and engineered nanomaterials [1, 74]. This heterogeneity makes it very difficult to monitor or model ecotoxins at large scales based on relationships with catchment development or physical processes. We therefore recommend further exploration of pressure-based proxies for the near-term, and that new research advances our understanding and modelling of persistence, fate and ecotoxicology of chemicals in river ecosystems [71].

Physical habitat

Four indicators are recommended to reflect physical habitat quality of rivers: connectivity, channel feature diversity, riparian vegetation, and instream vegetation. As with water quality, we find that several of these indicators are relatively well-situated for implementation at a global scale in the near future. However, unlike with water quality, this readiness is not due to the existence of *in situ* datasets but rather that physical aspects of rivers are more easily characterised from remote sensing data. As a result, anticipated increases in the resolution and capacity of remote sensing products will substantially improve our ability to measure these

indicators at a global scale (S1 Table). For example, recent launches of high-resolution global multispectral sensors have greatly advanced our ability to measure the extent and structure of riparian vegetation even for narrow riparian corridors, while hyperspectral sensors will increasingly enable species identification, to the extent of differentiating non-native species invasions or quantifying the prevalence of non-native species [75]. Launches of spaceborne LiDAR sensors will further improve this capacity [76], as well as the identification of channel feature diversity [77].

Metrics for assessing longitudinal connectivity (i.e., river fragmentation) at large scales are already well-developed [78]; however, the global datasets of river barriers that are needed to calculate these metrics are still highly incomplete [79]. Nonetheless, broader characterization of longitudinal barriers (i.e., beyond the current emphasis on relatively large dams, diversions and road crossings) is advancing with novel remote sensing techniques [80, 81] and manual mapping [82], including citizen-science based efforts [83]. Lateral connectivity is an important aspect of physical habitat that has lagged substantially behind measurement of longitudinal connectivity, but is poised for substantial advancement at the global scale [e.g., 84]. Higher-resolution remote sensing products will allow identification of lateral barriers and lateral surface water coverage and dynamics [85], while automated and machine learning approaches (e.g., convolutional neural networks) are increasing the accuracy of surface water classifications, resulting in improved capacity to characterise lateral connectivity at large scales [86, 87] and over time [88].

Although we predict consistent improvements in most physical habitat indicators based on higher resolution and better classification of remote sensing products, the exception to this trend is the characterization of instream vegetation, which is very challenging to assess remotely [89]. This is due to tradeoffs between spatial, temporal, spectral and radiometric resolution, all of which are needed for accurate estimation of aquatic vegetation. Aquatic plants are not routinely or comprehensively measured as part of large-scale monitoring programs, resulting in limited *in situ* datasets to support modelling and remote sensing classification training efforts. We recommend that developing this indicator will benefit most from modelling aquatic plant diversity and abundance based on hydrographic characteristics (e.g., discharge, floodplain extent, inundation) and nutrients [90, 91], supported by the anticipated expansion of hyperspectral imagery [89]. It is also possible that environmental DNA (eDNA) sampling—if conducted at large scales—might inform measurement of aquatic plant diversity [92]. However, development of eDNA for aquatic plants is behind even other freshwater taxonomic groups [93]; and the relation of eDNA with abundance of plants (and other biological organisms) seems likely to remain elusive for some time.

Hydrology

Our recommended framework includes two hydrologic indicators of river health, which are the extent of surface water and the degree of alteration from the natural flow regime. Both of these indicators currently are in a state of moderate readiness for implementation at a global scale, mostly due to a bias toward measuring large rivers, resulting in limited and inconsistent data to monitor extent and flow of small or intermittent streams [94]. However, both indicators are likely to gain substantially from recent and anticipated improvements in remote sensing products (S1 Table). Measurements of flow alteration are commonly included in large-scale monitoring based on national gauge systems; however, these systems disproportionately monitor large, perennial, developed, and regulated rivers [95]. Global availability of discharge measurements also depends greatly on the financial and technical capacity of countries to collect data, combined with their willingness and capacity to provide access [96, 97]. Despite

ongoing calls and resolutions for international gauge data sharing, logistical, financial, and administrative constraints have caused gauge networks and data contributions to consistently decline for several decades [95, 98]. Modelling of flow alteration at a global scale is plagued by both the limitations and availability of *in situ* data stated above, and challenges in downscaling models to reflect conditions in medium or small rivers [99, 100]. Though likely to require several decades of development—we advance that one of the most promising opportunities to improve accuracy and resolution of discharge is the emerging use of satellite altimetry, which will help fill data gaps for large and medium rivers [101]. For small (and medium) rivers, another important opportunity lies in community science initiatives to monitor streamflow, which can range from maintaining and monitoring fixed gauges [102, 103] to low-tech options for ungauged sites [104].

In contrast to streamflow, which has been routinely measured in some countries for more than a century, systematic mapping of surface water extent is only recently possible [105]; this indicator is therefore not well represented in large scale monitoring programs. Critical limitations in measurement of surface water at a global scale are the resolution of these remote sensing data, along with substantial challenges from overhanging and emergent vegetation and frozen, snow or glacial surfaces, which interfere with the optical properties of water [106]. For this reason, mapping of surface water extent for medium or small rivers has only become feasible with very recent launches of high-resolution sensors [85]. However, even these high-resolution products are unlikely to address the substantial issue of incorporating riverine wetland areas (i.e., riparian or forested), which may be permanently or seasonally inundated. Future development of this indicator that accounts for surface water across the full spectrum of riverine habitats will likely require a combined modelling approach based on classification of high-resolution remote sensing data and topographic analyses of wetland presence and extent [107, 108].

Discussion

We initiated this work in response to what is not only a dire situation for global river health monitoring, but where we believe the prognosis and trajectory for substantial improvement over time is currently uncertain. This position is supported by other strenuous calls for improvement in global monitoring and conservation of freshwater systems and biodiversity [9, 11, 36, 109]. However, we advance that important developments in policy and research have also set the stage for adoption and step-wise implementation of a global river health monitoring framework, which can support adaptive management and restoration for rivers at diverse levels of geographic organization (Fig 2).

A common framework to assess river health is a critical foundation to address global disparities in monitoring and evaluation. Regions and nations vary widely in the resources that they have available for this work, as well as the existence and structure of incentives [18]. An important outcome of a multi-scale framework is the ability to estimate river health in data-poor areas (albeit with more uncertainty), which can indicate geographic areas that should be prioritised for data collection, synthesis, and modelling [110]. As capacity grows to more accurately measure and compare the biophysical condition of rivers, at scales varying from reach to basin (Fig 2), so too does the ability to relate condition to anthropogenic pressures and impacts, and to underlying socio-economic conditions and cultural values [34]. Biophysical conditions can serve as a basic template into which human perspectives and valuing of rivers are subsequently incorporated as additional indicators. These indicators can be developed at national or local scales, as appropriate, and with the involvement of diverse stakeholders [26, 27].

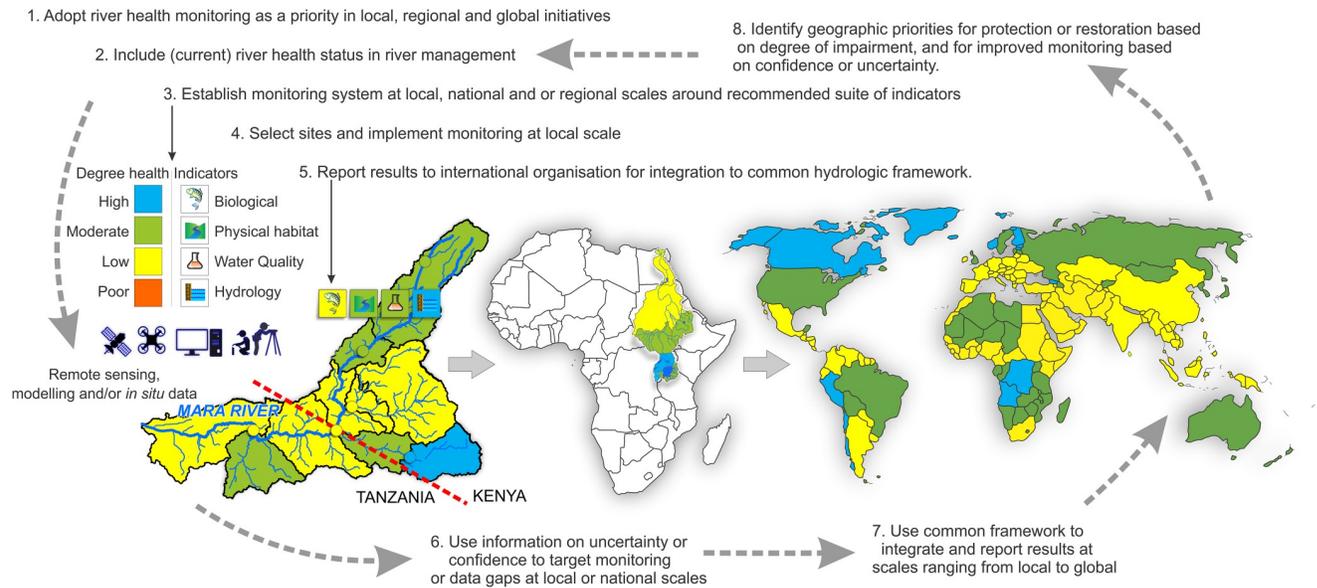


Fig 2. Implementing a global river health monitoring framework. Steps and associated benefits of implementing a river health framework that adaptively supports, coordinates, and integrates research and monitoring efforts from local to international scales. A common hydrographic framework provides the structure to integrate local monitoring (bottom-up) with regional or global data syntheses (top-down), and harmonise indicators across spatial scales. Degree of Health (represented by colours) based on indicators can be integrated at increasing scales, to inform prioritisation of investments for monitoring and restoration. [Note: Degree of Health shown in the figure is indicative only and does not represent quality for any region based on actual data]. Maps of the Nile Basin <https://www.hydrosheds.org/products/hydrobasins> [99] are reprinted with permission from the HydroBASINS Database, HydroSHEDS 2023. African continent <https://hub.arcgis.com/datasets/africa::africa-countries/about> [122] and world maps <https://hub.arcgis.com/datasets/esri::world-countries-generalized/about> [123] are reprinted with permission from Environmental Systems Research Institute, Inc., Esri Master License Agreement 7 Dec 2022.

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A global framework will also help address disparities in river health monitoring by providing a structure for global coordination of research and monitoring efforts. Effective river health monitoring, protection, and restoration crosses standard jurisdictions, which is why there are many efforts at not only national but also basin, trans-boundary basin and regional scales [111]. A strong global commitment to a suite of river health indicators (i.e., our proposed framework) can guide and support existing and developing programs and provide structure to integrate monitoring efforts at diverse scales (Fig 2) [35]. Such efforts may include the development of new monitoring tools, ranging from use of low-tech and/or citizen-science based gauging stations [e.g., CrowdHydrology, 104] to the development of new systems of governance or national monitoring programs [112]. A global framework can support and justify work by nations (or regions) that are engaged in or in a position to coordinate data gathering, synthesis, and evaluation toward a global agenda. Concurrently, international organisations and/or nations with resources can focus on the research gaps for global-scale indicators (Table 2)—many of which emphasise addressing data limitations in developing nations—when determining funding priorities.

Enabling factors

We see three fundamental factors needed to enable development and step-wise implementation of a global river health monitoring framework. First, we urge the adoption of river health monitoring and its benefits for sustainable water resource management as a priority within local, regional, and global initiatives (Steps 1–2, Fig 2). Rivers and river health warrant

protection not only for the considerable ecological and social benefits they confer, but for the strong concordance and linkages with terrestrial conservation and protection efforts. Conservation planning has historically segregated terrestrial, marine, and freshwater ecosystems, and favoured terrestrial priorities and biodiversity, which can generally be protected in defined spatially restricted reserves [113]. However, there is mounting evidence for the co-benefits of integrating freshwater conservation and biodiversity targets into terrestrial conservation planning [114, 115]. Specifically, because rivers are networks that connect habitats and integrate catchment conditions, actions that protect and restore rivers (and riparian areas) also benefit terrestrial ecosystems and biodiversity [116, 117], and it has been found that freshwater targets can be dramatically improved with only negligible risk for terrestrial targets [114, 118]. Regional and international agreements and conservation planning need to acknowledge and reflect the large contribution of rivers and river health to overall biodiversity.

Second, we recommend a resolute and coordinated focus to develop methods and synthesise data sources for the framework of indicators (Steps 3–4, Fig 2). Decades of large-scale monitoring programs support agreement on suitable indicators, and corresponding investment in their development for global scale implementation. This requires advancing data collection and synthesis for indicators, using methods that can range from incentivising individual scientists (and governments) to share local data, to improving the resolution and availability of remote sensing products [11]. The technologies that we have outlined could improve measurement of biophysical components (or specific indicators), but implementation at the global scale requires more than technical advancement. For example, eDNA—which can estimate aquatic species presence and/or abundance of some species—has the potential to dramatically improve the availability of *in situ* data for critically important biological indicators (Table 2). However, its use for global river health monitoring requires that the technology is accessible and widely used (i.e., outside of developed countries), and that there are platforms to synthesise eDNA data, based on agreed-upon standards of detection [52]. Similarly, machine-learning approaches, including artificial intelligence to automate classification of remote sensing data, have strong potential to advance and refine the measurement of physical habitat and hydrologic indicators [86, 88]. However, improving and implementing these approaches to assess river health requires interdisciplinary collaboration across fields of ecology, data science, and artificial intelligence.

As previously noted, a critical advancement toward global river monitoring is agreement on the use of a multi-scale framework [28, 29] with standardised spatial units of river reaches and catchments (Step 5, Fig 2). A common hydrographic framework would provide the geospatial foundation for developing recommended procedures for data collection (e.g., determination of local or regional sampling sites, synthesis, modelling methods) as well as a system for harmonising indicator data to visualize and compare ecosystem condition (Table 1). Together, a common spatial system and suite of indicators would allow individual governments and researchers working at local, national or regional scales to contribute environmental and monitoring data to the global framework (i.e., bottom-up). Concurrently, international organizations and researchers working at larger scales can focus efforts to develop and improve global data sources and methods to support and complement local and national efforts (i.e., top-down) (Steps 6–8, Fig 2).

This leads to our third recommendation, which is to identify and promote an international organisation responsible for the coordination of national or regional commitments and accountability. Simply stated, it is not possible for a national or even regional entity to coordinate the multi-scale efforts and diversity of actions needed, nor to sustain those efforts over the time scale that is required. We do not suggest that an international organisation would do all of the work, but would rather have accountability for finalising a framework, promoting and

coordinating research activities (e.g., data synthesis, modelling), housing data repositories and products (or coordinating solutions), fostering grassroots developments, and encouraging relevant national and regional policy [e.g., 112]. An international organisation would also be well-positioned to lead or support efforts by member countries or other entities to fund work that advances the global research agenda. Depending on the scale of the work, funding could be sought from national funding agencies, large foundations, or global funding organisations (e.g., World Bank, Global Environment Facility).

Previous examples of an international effort that could be emulated is the Global Forest Resource Assessment Program (FRA), housed within the United Nations Food and Agriculture Organization. Initiated in 1946, the FRA has conducted global forest assessments in cooperation with member countries, which has included identification and promotion of a common framework of indicators [119]. The process has evolved and matured over time, integrating new monitoring technologies and incorporating bottom-up efforts from a larger number of nations and stakeholders as they have been developed and are available [120, 121]. We recommend development of a similar initiative housed in an international program (e.g., the UN Environmental Programme, UN Food and Agriculture Organization) focused on river health monitoring. River health is inherently and inextricably intertwined with other environmental challenges that impact humans. An initiative to develop and improve a global river health framework would be well-positioned to work synergistically with other international initiatives, such as those focused on water security (e.g., the SDGs), biodiversity (e.g., IPBES, CBD), and climate change (e.g., the NDCs).

Applying the framework

The framework that we recommend is intended to support an adaptive process to monitor river health at a global scale. Importantly, we believe this process could result in an initial picture of global river health within the next 10 years, by 2030, a timeframe that is well-aligned to inform the anticipated review of international conventions (i.e., SDG and CBD). However, interim products could guide and inform current and emerging data monitoring, conservation, and restoration efforts. Monitoring that incorporates a majority of indicators could be implemented in data-rich areas to guide conservation and restoration planning at national or regional scales (Fig 2); these would serve as useful test cases for iterative design of outputs and products (e.g., river health scorecards) that could effectively inform policy and public communications. Initial assessments at a global scale could be implemented using a subset of indicators for which data resources are robust and confidence is high (Table 2, Fig 2). Such initial or interim assessments could contribute data toward indicators and targets that are already outlined in international conventions, but which are currently inadequately measured. These include SDG 6.6.1 [“Change in the extent of water-related ecosystems over time”], IPBES [“Nature” or “Nature’s benefits to people”], multiple articles within RAMSAR [Articles 2.1–2.5, 3.2, 4.3, etc] and multiple targets within the Kunming-Montreal Global Biodiversity Framework [draft Targets 1,2,3,5 and 9].

Summary and conclusions

Historical challenges and technological barriers have stymied our capacity to monitor and assess the health of river ecosystems at a global scale. These include a relative lack of conservation awareness for fresh waters, a focus on the extractive rather than ecosystem value of rivers, monitoring methods developed for local and national purposes, and challenges in applying large-scale (i.e., remote sensing) monitoring methods to rivers. Decades of large-scale monitoring combined with technological advancements can now support development of a

framework of indicators that represents the biophysical health of rivers at a global scale. However, widespread commitment to a framework is needed to focus and consolidate the monitoring approach, advance necessary research and data syntheses, and improve accuracy of these indicators over time. Through integration of bottom-up and top-down approaches, a consistent global framework will also provide critical support for river conservation and restoration efforts at scales ranging from local to international.

Supporting information

S1 Table. Data sources. Current sources and compilations of *in situ*, remote sensing (RS), and modelled datasets that would support development of the recommended indicators outlined in Table 2.

(DOCX)

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