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Perspective Article

Charting a course for freshwater biomonitoring: The grand challenges identified by the global scientific community

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1 We dedicate this work to the memory of Dr. Robert (Bob) Hughes who was a visionary leader in freshwater biomonitoring.

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ABSTRACT

The past 50 years have seen biomonitoring emerge as an essential means of generating the knowledge needed to inform protection and restoration of freshwater ecosystems. Despite the successes of biomonitoring, most freshwater ecosystems remain unmonitored. Moreover, degradation of freshwaters continues at a rapid rate with new threats and novel stressors emerging that are difficult to assess using existing techniques. New technologies and techniques have been developed to improve biomonitoring, but application has been slow and integration with existing approaches is often problematic. Clearly, freshwater biomonitoring faces many important challenges that must be addressed to meet management needs of the coming decades. We identify Grand Challenges facing freshwater biomonitoring with the aim of encouraging research and practice to address these challenges. We asked 256 biomonitoring scientists from around the globe to identify what they considered the most important challenges. From their submissions we established five Grand Challenges and 18 associated sub-challenges. For each Grand Challenge, we outline the current state of biomonitoring practice and suggest promising pathways and approaches to address them. By identifying and describing these challenges, we strive to position freshwater biomonitoring to take advantage of emerging opportunities and enhance its capacity to meet current and future management needs.

1. Introduction

Freshwater ecosystems provide critical services to society, such as water for drinking and irrigation, maintenance of habitats for wildlife, water purification and nutrient cycling (Finlayson et al., 2005; Postel and Carpenter, 1997). Increased recognition of the importance of these ecosystems has generated a need for improved understanding of freshwater health to inform management and restoration. This understanding has increasingly been generated through freshwater biomonitoring (i.e., estimation of the ecological health of freshwaters using organisms, biological communities and ecosystem processes) (Buss et al., 2014; Feio et al., 2021; Simaika et al., 2024). Yet, despite widespread biomonitoring that has enhanced understanding and management of ecosystem health, rapid degradation of freshwaters continues around the world. Degradation is driven by expanding and intensifying influences of often novel, interacting human pressures and associated stressors, as well as climate change (Birk et al., 2020; Dudgeon, 2019; Lynch et al., 2023; Reid et al., 2019). Moreover, these threats are often transboundary and/or occur where socio-economic barriers limit the capacity for, and accessibility to, contemporary biomonitoring approaches (Erős et al., 2023; Feio et al., 2023). Clearly, existing biomonitoring protocols and programs are insufficient to meet all current, and likely future, management needs.

These challenges for freshwater biomonitoring are arising during a period of unprecedented advances in ecological knowledge as well as rapid development of novel technologies and approaches that have the potential to transform freshwater biomonitoring. For example, new knowledge of linkages between biodiversity and ecosystem function has enabled scientists to effectively intersect ecological knowledge with ecosystem service concepts and generate enhanced ecosystem-based management strategies (Baert et al., 2016; O'Higgins et al., 2020; Teixeira et al., 2019; Woodward, 2009). Likewise, advances in remote and *in situ* sensors (Dörnhöfer and Oppelt, 2016; Kumar et al., 2024; Silva et al., 2022; Yang et al., 2022), and the emergence of 'Omics' technologies (Machuca-Sepúlveda et al., 2023; Pomfret et al., 2020; Zhang et al., 2018), are providing scientists with the tools to generate enhanced understanding of freshwater ecosystem diversity and function at all levels of the biological hierarchy (i.e., molecular to ecosystem) across increasingly large temporal and spatial extents. Yet, application of these advances has been limited, suggesting there are barriers to implementation that need to be identified and overcome.

Despite the significant accumulation of knowledge and technological advancements enabling freshwater biomonitoring to become a foundational component of ecosystem management, there are clearly challenges that remain. Although numerous papers have reviewed the state of specific aspects of freshwater biomonitoring (e.g., Buss et al., 2014; Keck et al., 2017; Machuca-Sepúlveda et al., 2023; Santos and Ferreira, 2020), those endeavours do not capture the biomonitoring community's perspective of the major gaps in knowledge and procedure. Therefore, our goal was to identify what the global biomonitoring community perceives as the Grand Challenges that need to be addressed to enable freshwater biomonitoring to effectively inform management of freshwaters around the globe in the coming decades. We achieved this goal by asking practitioners and users engaged in freshwater biomonitoring what they considered the most important challenges facing the advancement of freshwater biomonitoring. We also outline the current state of biomonitoring practice and provide ideas of promising future pathways and approaches to address these Grand Challenges. By identifying and describing these key challenges, our findings will better position freshwater biomonitoring to take advantage of emerging opportunities and enable it to meet management needs that arise in the coming decades.

2. Grand challenge identification and analysis

2.1. Challenge collection

We used an inclusive, two-step, horizon scan process adapted from Sutherland et al. (2013) to capture the diverse experiences and perspectives of freshwater biomonitoring practitioners and users. First, the project steering group (A.G. Yates, R.B. Brua, and J.M. Culp) used their biomonitoring practitioner and user networks to purposely identify potential participants. Identified individuals were invited to submit what they considered to be the Grand Challenges (up to five) of freshwater biomonitoring. Second, invited participants were asked to solicit and submit challenges from their own freshwater biomonitoring networks (invitation letter available in Supplement 1), initiating a phase of snowball sampling (Parker et al., 2019) to capture broader geographic,

Table 1
Five Grand Challenges for freshwater biomonitoring as derived from individual challenges submitted by practitioners and users working in freshwater biomonitoring. Subchallenges reflect more specific themes related to each Grand Challenge.

Grand Challenge	SubChallenges
Protocol Development: *Adapt and develop techniques and protocols that can enable assessment of existing and emerging stressors and pressures in a changing global environment*	1. Integrate advanced/new technologies and techniques (e.g., eDNA, remote sensing, modeling) into biomonitoring 2. Develop biomonitoring protocols for under-assessed ecosystems (e.g., intermittent streams, wetlands) 3. Develop protocols and metrics for assessing climate change impacts on freshwater ecosystems 4. Develop techniques that account for shifting baselines/reference conditions arising from climate change 5. Develop and implement causal assessment methods that can disentangle effects of multiple stressors enabling diagnosis of the cause(s) of poor biological conditions
Construct Infrastructure: *Construct and maintain globally interoperable freshwater biomonitoring infrastructure*	1. Commitment to sufficient and sustained funding to develop, implement and maintain freshwater biomonitoring programmes 2. Establish legislation that requires biomonitoring to assess and report on freshwater ecosystem quality as well as activate management action when required 3. Build and maintain the expertise (e.g., taxonomy; field sampling) required to develop and support biomonitoring in all regions of the globe 4. Harmonize biomonitoring protocols (e.g., inter-comparability of methods; sampling; targeted endpoints) that promote collection of broadly comparable data enabling transboundary, regional and global scale assessments
Holistic Ecological Context: *Expand freshwater biomonitoring to holistically represent ecological context*	1. Enhance basic ecological understanding of how biota in all freshwater ecosystems (e.g., groundwater; intermittent streams; estuaries, wetlands) respond to human induced environmental changes associated with individual, multiple, and emerging stressors 2. More fully integrate theoretical ecological principles (e.g., metacommunities; niche theory; species interactions) into freshwater biomonitoring programmes 3. Expand freshwater biomonitoring to be more inclusive of aspects of ecosystem structure (e.g., meiofauna, microbes) and function (e.g., nutrient cycling; organic matter processing; traits)
Empower Communities: *Empower all communities to meaningfully engage in all facets of freshwater biomonitoring*	1. Increase opportunities for Indigenous and Local Communities to co-develop and lead community-based freshwater biomonitoring that are meaningfully linked with regional/national programs 2. Empower decision makers, stakeholders, indigenous and/or local communities to meaningfully engage with freshwater biomonitoring programs by mobilizing and communicating knowledge and data 3. Increase collaboration and coordination within and among government, academia, NGOs, and Indigenous Peoples and Local Communities to facilitate biomonitoring activities that are efficient, socially and environmentally relevant, as well as cost-effective
FAIR Data: *Ensure freshwater biomonitoring data meet the FAIR principles (findable, accessible, interoperable, and reusable)*	1. Increase the findability and accessibility of data for humans and computers by ensuring metadata is searchable using open protocols 2. Ensure that databases are interoperable 3. Optimise reuse of data by enabling replication and/or combination of data in multiple settings.

sectorial, and experiential perspectives.

To minimize the influence of biases introduced by the steering group, participants were unconstrained with regards to the form and content of submitted challenges. Participants were encouraged to solicit challenges from all sectors of freshwater biomonitoring in their respective regions to maximize the diversity of perspectives represented. All individuals who contributed to the snowball sampling by collecting challenges from their own networks were invited to co-author this manuscript. Participants were asked to indicate their country of employment, employment sector, and role in biomonitoring.

2.2. Limitations and caveats to challenge solicitation

Our study was limited to individuals actively participating in freshwater biomonitoring. Consequently, the perspectives of individuals currently excluded from biomonitoring activities are not represented in our list of challenges. An individual's demographics may affect their views, and we do not know the degree to which the demographics of the people who expressed topics reflect the demographics of all people working in freshwater biomonitoring. Indeed, we did not gather information on many personal characteristics (e.g., education level, gender and age) that may have influenced the challenges contributors chose to submit. Based on the contributor information we did collect (i.e., continent, sector and role), it was apparent that participation was skewed towards researchers working in academia from countries in Europe and South America. Although the variation in participation may partially reflect the current distribution of individuals involved in biomonitoring, it is also likely that limited representation of many groups stemmed from unintended biases in our sampling approach. For example, the predominance of researchers in our study almost certainly reflects biases of association (i.e., researchers are more likely to have researchers in their networks), but also likely a capacity bias (i.e., flexibility in work schedule to participate). Similarly, language and cultural barriers to participation may have contributed to the differences among continents. Despite these potential limitations, our study provides the broadest investigation of perspectives on challenges facing freshwater biomonitoring.

2.3. Challenge analysis

Submitted challenges (N = 1052) were collated and reviewed by the steering group and challenges unrelated to freshwater biomonitoring removed (n = 18). The retained 1034 challenges were assessed to identify common themes. We did not attempt to consider the importance or uniqueness of the challenges. Each steering group member independently made lists of the themes that they considered to occur most frequently. Lists of themes were then compared, and all unique themes included in a new list. To ensure that no major themes were missed, all 1034 challenges were submitted to OpenAI ChatGPT 4.0 (March 23, 2023) for text pattern analysis, with the instruction, "Identify and provide an annotated list of the major themes in the submissions". This process produced seven themes, all of which the steering group had identified (Table S1). As a result, only the steering group's list of identified themes was reviewed further and overlapping themes were identified and combined. The final list included five Grand Challenges that captured the thematic scope and frequency of the submissions. For each

Grand Challenge, a series of subchallenges was identified by selecting, and in some cases combining, retained challenges that reflected the specific, core aspects of each Grand Challenge. From this process, we identified five Grand Challenges and 18 associated subchallenges (Table 1).

To link contributor attributes to the Grand Challenges, the steering group first re-reviewed the 1034 retained challenges and assigned each to the Grand Challenge(s) that best captured its thematic elements. Because retained challenges sometimes included multiple themes, submissions were assigned to up to two Grand Challenges. The steering group also classified participants based on their country of employment and each contributor was assigned to a continent. Employment sector was categorized as academia, government, not-for-profit, private sector, or unknown/other (Table S2). Roles in biomonitoring were limited to researcher, practitioner, manager, or unknown/other. We determined the frequency and relative frequency of retained challenges reflecting each of the Grand Challenges for each designated group.

2.4. Challenge classification and assessment

Challenges were submitted by 256 contributors working in freshwater biomonitoring in 40 countries. Submissions were obtained from all inhabited continents with 61 % of submissions originating from Europe and South America (Fig. 1A). European submissions were from 15 countries, whereas 83 % of submissions from South America originated from Brazil. Africa, Asia and Oceania each generated 6–8 % of submissions. Researchers, practitioners and managers submitted 68 %, 20 % and 11 % of the challenges (Fig. 1B). Similarly, submissions were predominantly from individuals working in the academic (57 %) and government (32 %) sectors (Fig. 1C).

Sixty-three percent of the retained challenges were linked to one or both of Protocol Development and Construct Infrastructure (Fig. 2). In contrast, challenges related to Empower Communities and FAIR (Findable, Accessible, Interoperable, and Reusable) Data comprised 16 % of the total submissions. Holistic Ecological Context was addressed in 21 % of the submissions.

Participants in Africa and Asia most frequently identified challenges related to Construct Infrastructure, whereas challenges related to Protocol Development were most identified in the other continents (Fig. 3A). Incorporating FAIR Data principles into biomonitoring was least frequently identified for all continents, except Asia. Empower Communities was almost twice as often identified by Africans and North Americans compared to other continents. Holistic Ecological Context was more often identified by Europeans than by participants from other continents, especially Africa, Asia and South America.

Submissions from managers, practitioners, and researchers were similar in the frequency with which challenges were cited (Fig. 3B), although managers cited Holistic Ecological Context and Construct Infrastructure challenges less and more frequently than the other roles, respectively. The frequency of challenges identified by individuals in academia and government were similar (Fig. 3C), whereas the not-for-profit sector most often identified challenges related to Construct Infrastructure or Empower Communities and the private sector identified Protocol Development and Construct Infrastructure most frequently.

3. Discussion of grand challenges

3.1. Protocol development

Numerous submissions cited the challenge of developing biomonitoring protocols for under-monitored or unmonitored ecosystem types (e.g., intermittent streams, groundwaters and some wetland types). The absence of system-specific protocols has resulted in lower representation of these ecosystems in biomonitoring programs (Stubbington et al., 2018), or their assessment using methods developed for other ecosystems (Lorenz et al., 2023; Mazor et al., 2014; Pignata et al., 2013). Consequently, reliable assessments of the status of many freshwater ecosystem types cannot currently be achieved. These protocol gaps may be filled through adaptation and validation of existing biomonitoring or research methods used in other ecosystems (Datry et al., 2014). However, methods designed for specific ecosystem types may produce more robust assessment outcomes (Steward et al., 2018; Stubbington et al., 2019), warranting further research to inform development of sampling and assessment protocols that may vary within and between biogeographic regions (Erős et al., 2023).

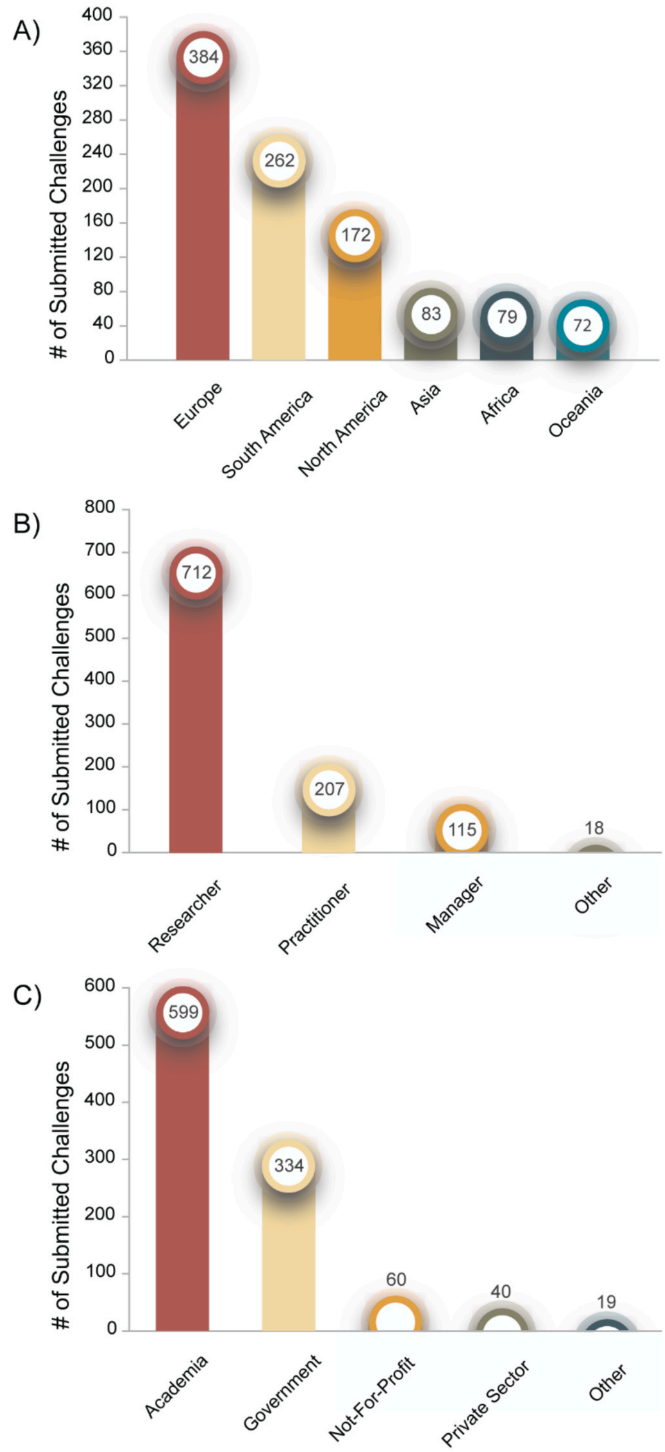

Fig. 1. Number of freshwater biomonitoring challenges submitted (N = 1052) by continent (A), role (B) and sector (C).

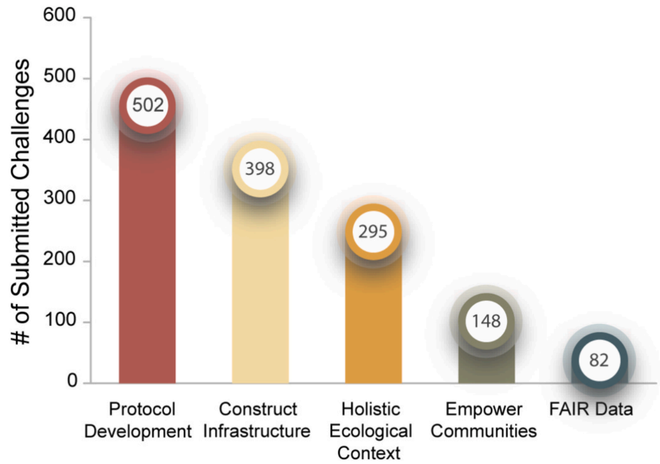

Fig. 2. Frequency of assignment of retained challenges (N = 1034) to Grand Challenges. Retained challenges were assigned to one or two Grand Challenges, resulting in a total greater than the number of submitted challenges (N = 1425).

Submitted challenges highlighted opportunities to enhance biomonitoring using new technologies, especially Omics and sensor technologies. eDNA-based metabarcoding and associated technologies are increasingly used to generate comprehensive descriptions of community composition (Compson et al., 2020; Robinson et al., 2022), identify at-risk and invasive species (Currier et al., 2018; Morisette et al., 2021), and upscale local assessments of river status (Blackman et al., 2024). Other promising Omics technologies include environmental metabolomics, to better diagnose causes of biological degradation (Pomfret et al., 2020), and metagenomic techniques that provide insight into ecosystem functions associated with microbial communities (Fasching et al., 2020; Rodríguez-Ramos et al., 2022). Likewise, advances in remote and *in situ* sensors have the potential to expand the spatio-temporal scope and resolution of biomonitoring. Indeed, advances in Earth observing instruments have increased the range of ecological parameters effectively monitored using remote sensing (Ustin and Middleton, 2021), enabling near-real-time monitoring of whole ecosystem change (Binding et al., 2021). Concurrent improvements in the quality and range of parameters measured (e.g., Chlorophyll *a*, dissolved oxygen) by *in situ* sensor technologies has also facilitated increases in the frequency and scope of biomonitoring (Jackson et al., 2016; Marcé et al., 2016). For example, increasingly affordable oxygen sensors are enabling monitoring of stream metabolism at spatio-temporal scales relevant to management (Appling et al., 2018).

Although novel technologies present significant opportunities to expand and enhance biomonitoring practice, participants also recognized the challenge that validation and integration of technologies pose. Indeed, few Omics technologies have progressed beyond the research phase and more advanced techniques, such as eDNA, still have technical (e.g., varying detectability of taxonomic groups) and operational (e.g., comparability with existing biomonitoring approaches) impediments needing to be addressed to operationalize this technology into biomonitoring (Makiola et al., 2020; Pawlowski et al., 2021). Integration of new technologies also poses a challenge in terms of maintaining continuity in datasets. New technologies must therefore undergo a calibration phase to quantify biases/inaccuracies and apply adjustments or transformations to data that enable assessment of long-term trends despite changes in methods (Blancher et al., 2022). Lastly, many technologies have the potential to increase costs of biomonitoring due to high purchase and maintenance costs of sensors and laboratory equipment. Accessibility of these technologies may therefore continue to be a barrier to widespread use, especially for less economically advantaged countries and communities.

Submissions frequently referenced the challenge of developing

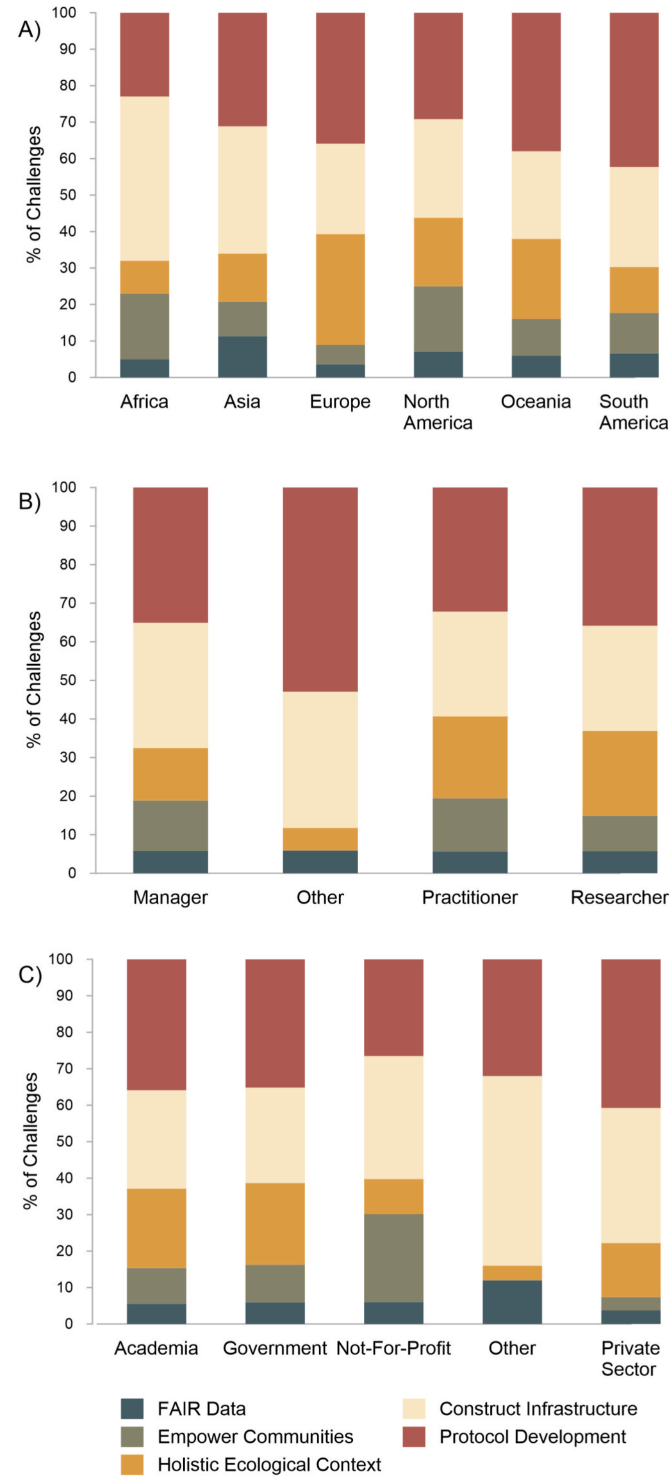

Fig. 3. Relative frequency of assignment of submitted challenges to Grand Challenges based on the continent (A), role (B), and sector (C) of the participant. FAIR = findable, accessible, interoperable, and reusable.

adequate baselines for assessment of change in freshwater ecosystems. Most contemporary assessment frameworks use a reference condition approach (Bailey et al., 2004), reflecting a widespread lack of historical monitoring data to serve as a temporal benchmark. Characterizing reference conditions is hampered by widespread historical and/or current human activity, the need to sample large numbers of ecosystems (e.g., multiple rivers or lakes), and the lack of appropriate reference analogs for many ecosystems (e.g., large rivers and lakes).

Paleolimnological techniques can help overcome the lack of historical monitoring data to establish baselines in some lakes and wetlands, albeit with noted caveats (Bennion et al., 2011; Hübener et al., 2015), but are less effective in lotic ecosystems that do not preserve intact sediment profiles. Modelling techniques (Leitão et al., 2018; Poikāne et al., 2010), as well as utilitarian definitions of reference condition, such as best attainable conditions (Stoddard et al., 2006), or ecosystem service provision (Yates et al., 2019), can establish baseline conditions where few or no minimally disturbed reference sites exist.

Many participants noted that climate change is hampering identification and maintenance of ecological benchmarks, or reference conditions, arising from altered ecosystems conditions (e.g., water temperature and hydrologic regime) and concomitant changes in species ranges and diversity. Changes in reference condition can lead to unintentional acceptance of a more degraded condition as the benchmark for management and restoration (i.e., shifting baseline syndrome; Klein and Thurstan, 2016; Pauly, 1995; Soga and Gaston, 2018)). Regions with a strong history of monitoring reference sites may be able to mitigate the effects of changing benchmarks by using past conditions to conduct future assessments of the impacts of human activities. However, most regions lack long-term monitoring programs and will thus need to use contemporary definitions of reference condition as the assessment benchmark.

Numerous submissions highlighted the need for protocols that effectively identify effects of changing climate conditions on freshwater biota. This is particularly problematic for rivers because of the poor suitability of paleolimnological techniques, limiting impact detection to sustained, long-term sampling programs conducted at sites in protected areas minimally exposed to other human impacts (Larsen et al., 2024). Although imperfect, due to atmospheric transport and contaminant deposition (Allen et al., 2019; Landers et al., 2010), or fluvial transport from upstream sources (Wolfram et al., 2023), the establishment of long-term studies in protected areas could enable monitoring of responses to future change. A potential path forward is the use of climate change vulnerability assessments. These assessments establish expected biological conditions under climate change scenarios that could be compared with biomonitoring observations (Woznicki et al., 2016). However, as most freshwater ecosystems are also exposed to other stressors and natural sources of variation (e.g., climate oscillations), new methods, or novel applications of existing methods, will also be needed.

Many submissions identified the challenge of diagnosing the effects of specific pressures and stressors. Indeed, many freshwater biomonitoring indices, especially in rivers, are designed to detect ecological degradation from multiple pressures and thus cannot easily diagnose cause in environments where multiple stressors produce similar effects (Herlihy et al., 2020; Rico et al., 2016; Schinegger et al., 2016). Indices with the potential to diagnose impacts from a specific stressor are less common (Poikane et al., 2020a), although exceptions include the species at risk (SPEAR) indices (Liess et al., 2017; Liess and Ohe, 2005; Schafer et al., 2011). In contrast, stressor-specific methods exist in lakes to assess eutrophication and acidification (Poikane et al., 2020a), although methods for several other pressures, such as salinization (Kelly et al., 2024), brownification (Horppila et al., 2024) and hydromorphological alterations (Poikane et al., 2020b), are less well developed. Further development of biomonitoring indices and protocols that can establish the cause(s) of poor condition would facilitate directed management and restoration strategies. Potential starting points to determine the stressors and pressures leading to poor biological conditions include pressure analyses, an integral part of waterbody assessments done for the European Union's Water Framework Directive 2000/60/EC (WFD; European Commission, 2000), or relative risk assessments (Herlihy et al., 2020; Van Sickle and Paulsen, 2008).

3.2. Construct infrastructure

Submitted challenges that were related to construction of biomonitoring infrastructure stem from a lack of policy and legislation that institutionalizes biomonitoring. Indeed, participants in Africa and Asia were substantially more likely to identify challenges relating to the need for legal infrastructure to underpin freshwater biomonitoring programs than participants in Europe where monitoring is directed by the WFD. Cascading from the lack of legislation is the challenge of funding the development and maintenance of biomonitoring activities as noted by many colleagues in the Global South, as well as some in the Global North (e.g., Canada), where legislation for biomonitoring is limited (Feio et al., 2021; Box 1). The lack of funding also limits development and maintenance of human infrastructure in the form of reduced impetus and capacity for training personnel with the expertise to conduct biomonitoring (e.g., taxonomists, field technicians, database managers, and data analysts).

The challenge of harmonizing biomonitoring activities across jurisdictional boundaries was recognized by participants. Limited comparability of biomonitoring data hinders efficient freshwater management and regional/global assessments (Feio et al., 2023; Simaika et al., 2024) and has prevented production of the World Water Quality Assessment requested by United Nations Environment Assembly (UNEA) Resolution 3/10 "Addressing water pollution to protect and restore water-related ecosystems" (UNEP/EA.3/Res.10). International legislation has proven to be a strong means of overcoming this challenge. For example, the European Union WFD requires that biological assessment methods are inter-calibrated and has resulted in the ability to assimilate biomonitoring data from over 300 different methods to generate continental-scale status reports (Poikane et al., 2015). Similar legislation within and between nations could initiate harmonized biomonitoring and enable assessments of major river basins. However, in the absence of international policy, grassroots initiatives, such as The Group on Earth Observations Biodiversity Observation Network's (GEO BON) Global Biodiversity Observing System to monitor Earth's biodiversity (Scholes et al., 2012), may provide the initial infrastructure to begin harmonizing biomonitoring (geobon.org).

Several submitted challenges noted the significant regional and national inequity in the availability of biomonitoring infrastructure and opportunity to participate in biomonitoring. The exclusion of many regions reduces understanding of the global condition of freshwaters and impedes the *trans*-jurisdictional management needed to effectively protect major rivers and great lakes (Feio et al., 2021; Simaika et al., 2024). Submitted challenges noted excluded regions often include developing countries, but also remote areas of developed countries with greater proportions of Indigenous peoples (e.g., Canadian Arctic). Moreover, socio-economic factors that frequently restrict opportunities to participate in biomonitoring also cause communities in these regions to be disproportionately affected by ecosystem degradation. Addressing these inequities is a challenge that extends beyond biomonitoring, although progress has been made through internationally-led training and transfer of techniques and knowledge (Resh, 2007). However, challenges submitted by African and South American participants frequently noted the need to develop region-specific techniques and capacities, including use of local languages. Increasing national and international collaboration and coordination among governments, non-government agencies and academia, as well as shifting from discipline-specific biomonitoring towards a more inclusive structure, could increase capacities in all jurisdictions through reduced duplication of efforts and more efficient resource use (Abernethy et al., 2020).

3.3. Holistic ecological context

Numerous participants noted how freshwater biomonitoring is strongly skewed towards a subset of ecosystem types, especially lakes and wadeable rivers, whereas other freshwaters including some wetlands, springs and groundwater, as well as intermittent streams, are less well represented. These under-monitored ecosystems often provide biodiversity and ecosystem services at a level disproportionate to their

Box 1
Illustration of Role of Legislation in Construction of Biomonitoring Infrastructure.

An illustration of the importance of legislation to the implementation and maintenance of biomonitoring infrastructure is the difference between the United States and Canadian Water Acts. The USA Clean Water Act objective "is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" and stipulates biennial reporting on water resource quality. The inclusion of biological integrity necessitates systematic biomonitoring, which led to comparable biomonitoring protocols nationwide (Feio et al., 2021; Herlihy et al., 2020). In contrast, the Canada Water Act lacks any specific phrasing regarding the maintenance of water resource quality and especially biological components. Instead, a series of disparate legislation protects Canadian freshwaters, leading to a patchwork of often underfunded, uncoordinated and discontinuous biomonitoring programs across the country (Feio et al., 2021). As a result, comprehensive assessments of the biological condition of freshwaters cannot be reliably completed in Canada at the national scale.

physical size (Blackwell and Pilgrim, 2011; Sulliván et al., 2025), in part because they host rare/threatened taxa (Colvin et al., 2019; Richardson et al., 2015). Assessing the condition of these ecosystems is therefore essential to promote protection through informed management (Di Lorenzo et al., 2024). The limited representation of many freshwater ecosystem types in biomonitoring is being addressed in some regions. For example, networks to monitor small streams and groundwater ecology are being established in the UK (Stubbington et al., 2025; Johns and Robertson, 2022). Similarly, the USA has a National Wetland Condition Assessment Program that reports on wetland health every five years (Kentula and Paulsen, 2019).

Submitted challenges noted that biomonitoring programs typically emphasize sampling and assessment of a small set of common (e.g., benthic macroinvertebrates) or charismatic (e.g., fish) assemblages (Friberg et al., 2011; Poikane et al., 2015; Vitecek et al., 2021). Other assemblages, especially microbial communities, are under-sampled despite evidence that such groups respond differently to changes in physical, chemical, thermal, and hydraulic habitats and that sampling one group may not capture the effects of all stressors (Herlihy et al., 2020; Moi et al., 2024; Ruaro et al., 2024; Solimini et al., 2009). Similarly, ecosystem processes and services are infrequently monitored (Solimini et al., 2009; Truchy et al., 2022; Yates et al., 2019). As a result, understanding of ecosystem condition is limited. Moreover, changes in measures of ecosystem structure (e.g., community composition) often do not reflect the condition of ecosystem functions (e.g., nutrient cycling, carbon processing; Feckler and Bundschuh, 2020; Kefford et al., 2024) and *vice versa* (Death and Collier, 2010; Sandin and Solomini, 2009; Yates et al., 2014). This contradicts the assumption that protection of ecosystem structure also protects function and supports calls for incorporating functional measures into biomonitoring programs (Brucet et al., 2013; Palmer and Febria, 2012; Von Schiller et al., 2017).

Current biomonitoring programs are largely grounded in perspectives of species sorting and niche theory (Cid et al., 2020; Leboucher et al., 2021). However, submitted challenges often indicated a need to include a greater range of ecological theories to inform a more robust interpretation of biomonitoring data with the integration of principles of metacommunity ecology often cited. Incorporating principles of metacommunity ecology could move biomonitoring beyond an ecological niche-based view to offer greater insight into where and why indices do not perform well. For example, stressor effects can be masked by colonization of impacted sites by sensitive taxa dispersing from unimpacted sites (i.e., mass effects; Bried and Vilmi, 2022; Heino, 2013; Leboucher et al., 2021). Additionally, metacommunity perspectives would allow freshwaters to be monitored as complex networks of interconnected habitats in a landscape context rather than in isolation. Metacommunity perspectives could be integrated into a biomonitoring framework, thereby adjusting expected ecosystem conditions in accordance with spatial connectivity and intermittency of assessment sites (Cid et al., 2020). Further conceptualization of freshwater biomonitoring in a *meta*-ecosystem framework (Cid et al., 2022) may also enhance biomonitoring outcomes given that many human pressures act at regional to global extents (Dudgeon, 2019).

3.4. Empower communities

Government agencies and academics have often led freshwater biomonitoring through the development and application of regulatory frameworks with limited engagement of local and Indigenous communities. Although this is changing (Gurnell et al., 2019), multiple submissions noted the need to more meaningfully include communities in biomonitoring. Exclusion of communities from the biomonitoring process limits awareness of programs and their goals, leading to public disinterest or distrust (Brooks et al., 2019). As a result, biomonitoring may be impeded directly through prevention of access to private lands or reduced support for management actions arising from biomonitoring results and indirectly by a lack of public pressure to develop policies and commit resources to initiate or maintain biomonitoring infrastructure. Biomonitoring would thus benefit from Indigenous and local communities being actively empowered to meaningfully engage with programs.

An increasingly common way for communities to engage with biomonitoring is through community-based monitoring (CBM; a.k.a., citizen science) initiatives (Brooks et al., 2019; Kitaka et al., 2024; Storey and Wright-Stow, 2017; Thompson et al., 2020). CBM of freshwaters ranges from application of regulatory monitoring protocols, to implementation of simplified, qualitative methods (França et al., 2019) and the use of mobile phone apps (Collins et al., 2023; França et al., 2019; Gurnell et al., 2019). Yet, despite growing popularity of CBM, these programs frequently operate in parallel to regulatory biomonitoring programs and communities are often only involved in the data collection phase (Schölvinck et al., 2022). Indeed, submitted challenges frequently cited the need to more fully integrate CBM and regulatory programs and to more effectively use the data CBM programs generate. Limited integration of regulatory and CBM programs constrains the potential for CBM outcomes to influence management and policy and creates appearances of elitism and feelings of exclusion and distrust amongst community members (Ball et al., 2022; Walker et al., 2021). Indeed, simply collaborating or improving engagement with communities on biomonitoring programs may be less effective than devolving authority to them and including communities in all phases of biomonitoring (i.e., program development, implementation, maintenance and reporting; Ball et al., 2022). Advantages of community participation in all biomonitoring phases include increased community engagement and awareness of freshwater issues, weaving of Western Science with local/Indigenous Knowledge, identification of indicators that better address local problems, and greater biomonitoring capacity (Thompson et al., 2020; Walker et al., 2021). However, integration of CBM requires intentional construction and maintenance of structures and frameworks through which collaboration and coordination can occur (Schölvinck et al., 2022), as well as ensuring that socio-economic factors do not limit engagement (Metcalfe et al., 2022).

Many participants acknowledged the need to enhance communication of biomonitoring results and data to communities. Transferring knowledge of the condition of freshwaters in a community's locality, region and/or country is essential to encouraging engagement as it generates awareness of threats to valued ecosystems (Brooks et al., 2019). Biomonitoring outcomes have often been inaccessible because of limited and/or unsuccessful dissemination, as well as use of overly complicated taxa lists and statistical analyses. However, knowledge transfer is improving with the adoption of techniques, such as report cards (Connolly et al., 2013) and guiding images (Kelly, 2012; Poikane et al., 2018), which can effectively summarize complex data and provide relatable images of what healthy and unhealthy ecosystems 'look like'. However, community awareness of biomonitoring outcomes is still often limited and finding effective approaches to increasing the reach of mobilization activities remains an important challenge.

3.5. FAIR data

The goal of freshwater biomonitoring is to collect data that can be used to determine ecosystem conditions and inform management strategies that maintain or rehabilitate their services and condition. In recognition of this, participants frequently submitted challenges related to making biomonitoring data FAIR (findable, accessible, interoperable, and reusable; Wilkinson et al., 2016). Development of databases, especially open databases, was frequently cited in the submitted challenges. Many biomonitoring programs have met this aspect of FAIR data (Schmidt-Kloiber and De Wever, 2018). However, barriers remain to both publishing and using open data (Beno et al., 2017). For example, inadequate and unstandardized metadata can limit use and reuse of open biomonitoring data (Bayer et al., 2023; Beno et al., 2017). Indeed, submissions often noted transboundary assessments as challenging because databases are not interoperable, calling for a harmonization of data systems among biomonitoring programs. Harmonization of data and metadata may be supported using international data standards, such as Darwin Core (Wieczorek et al., 2012), although the application of such standards to freshwater data requires guidance to ensure relevant data fields are included and that the database can support assessment (Lento et al., 2022). Moreover, achieving interoperability across databases will require implementation of rigorous quality assurance and quality control measures to maintain the integrity of biomonitoring data, including standard operating procedures. Although meeting criteria of findability, accessibility and interoperability will enhance the reusability of data, database reusability is frequently threatened by a lack of long-term funding (Costello et al., 2014), demonstrating how addressing the challenge of FAIR data goes beyond the character of the database.

4. Conclusions and outlook

Our assessment of the submitted challenges and synthesis of the Grand Challenges and associated subchallenges revealed clear linkages among the activities required to meet these challenges. Indeed, addressing many identified challenges requires that other challenges be addressed first. For example, addressing the challenge of understanding how biota in under-represented ecosystem types respond to human pressures and associated stressors will inform the development of biomonitoring protocols for these ecosystems. Furthermore, addressing one challenge may also facilitate addressing remaining challenges, but it must be ensured that addressing a challenge does not hinder the ability to address other challenges. For example, the adoption of higher-cost technologies may exacerbate socio-economic barriers to implementation in many regions and communities.

Given the potential for positive and negative impacts related to addressing specific challenges the approaches taken to address challenges requires careful consideration to maximize cascading benefits to freshwater biomonitoring systems. We thus argue that the first step is the development of a coordinated framework to address and prioritize the identified challenges. Although the framework needs to be tailored for specific regions/programs to account for current situations and future goals, an inclusive, *trans*-disciplinary process will best enable construction and implementation of these plans. A pressing challenge for all regions to initiate this process is empowering all communities to meaningfully engage in freshwater biomonitoring. Meeting this grand challenge will assist in the construction and long-term maintenance of essential infrastructure, facilitating the enhancement of freshwater biomonitoring practices.

CRediT authorship contribution statement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113646.

Data availability

No data was used for the research described in the article.

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