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Empowering citizen scientists to improve water quality: from monitoring to action

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Citizen science (CS) has so far failed to achieve its potential to contribute to water resource management globally despite a significant body of work proclaiming the benefits of such an approach. Also, this work has addressed concerns over precision, accuracy and reliability of methods used. This article presents the findings of a hackathon-type workshop challenge that brought together water quality experts and CS practitioners to explore barriers and possible solutions to mainstream citizen scientist-generated data into national, regional, and global reporting processes, and thereby provide a tangible connection between policy makers and community-based citizen scientists. We present the findings here as a perspective-type summary. This workshop challenge highlighted the breadth and scope of CS activities globally yet recognized that their potential for positive impact is going unrealized. The challenge team proposed that impact could be improved by: developing awareness; applying a simultaneous bottom-up/top-down approach to increase success rates; that local leaders or 'catalysts' are key to initiate and sustain activities; that generated data need to fulfill a purpose and create required information, and ultimately, lead to actions (data > information > action); recognizing that we are all potential citizen scientists is important; recognizing that "good water quality" is subjective; and lastly that developing a communication gateway that allows bi-directional data and information transfer is essential.

KEYWORDS

water quality, citizen science, SDG 6, water quality data, sustainable development goals, policy

1 Introduction

Water quality monitoring and assessment is an essential prerequisite for sound and robust water resource management. Monitoring objectives, which dictate the monitoring program design can vary, but to understand how the triple planetary crisis of climate change, biodiversity loss and pollution is impacting our freshwaters, the ecosystems they support, and the essential ecosystem services upon which we rely—monitoring programs that deliver long-term, and spatially diverse trend information are required.

The capacity of national authorities tasked with gathering this information varies greatly at the global scale. Many national authorities, especially those in low-income countries, lack the capacity to collect water quality data at the requisite spatial and temporal scales to provide science-based information for water resource management decisions. This deficit of water quality information has been made clear through countries' reporting on SDG indicator 6.3.2 on ambient water quality. In 2021, it was reported that just 1.7 per cent (1,300) of the total water bodies reported on (77,000) were from the lowest income quartile group of UN Member States (UNEP, 2021). At its most basic, reporting on this SDG indicator requires *in situ* water quality data to be collected on basic physico-chemical parameters from designated monitoring locations on a defined sample collection schedule. A much greater long-term monitoring and assessment capacity is required if countries are to fully understand the pressures and stresses placed upon their water resources than is prescribed by this SDG indicator, but this basic methodology serves as a useful first step and benchmark for countries that are developing and advancing this capacity.

The potential of CS as an effective means to contribute to SDG monitoring is widely recognized (Fritz et al., 2019; Fraisl et al., 2020; Ballerini and Bergh, 2021). In addition to data provision for water governance, CS also provides opportunities around engagement, education, awareness raising, and action in favor of water quality. CS as a means to fill the water quality data gap has been presented as an alternative data stream for national and global reporting (Bishop et al., 2020; Hegarty et al., 2021). As of yet, this potential has not been realized and CS-generated data have so far not contributed to national monitoring systems, nor to water-related regional or global reporting frameworks such as the SDG 6.

Citizen scientists employ various approaches and methods to monitoring (Blanco-Ramírez et al., 2023), and although concerns over accuracy, precision and reliability of citizen-generated data have been considered in several studies (Quinlivan et al., 2019; Moshi et al., 2022; Stankiewicz et al., 2023), still, there remain barriers to the use of these data. Much work has been done by scientists who have used CS as a strategy for data collection or focused on data accuracy comparisons, by non-governmental organizations or by other local or community groups which have not necessarily impacted the national and political scale for water quality reports. However, their work mostly informs scientist or citizen scientists needs, and much less to enable water governance, civil servants and policy makers to make use and benefit from CS data and its potential.

This article explores the various barriers to incorporate citizen-generated data into national reporting systems and proposes potential solutions to overcome these barriers and thereby empowering the citizen scientists to improve the water quality of their water resources.

2 Innovation workshop on water quality monitoring and assessment

Over 3 days, during a face-to-face workshop in Petten, the Netherlands, the authors of this paper discussed the use of CS for water quality monitoring. Experts from different world regions (Brazil, Cameroon, Costa Rica, Guatemala, Italy, Kenya, the Netherlands, Pakistan, Peru, Sierra Leone, and Switzerland), worked together to define the barriers that are still being faced to include citizen-generated data in national regional and global reporting. This team included civil servants, scientists, UN-officials, non-governmental organization, and the small-medium enterprise sector. The team worked together during to define what needs to be done to include CS in national regional and global reporting. The uniqueness of this assembly of roles, expertise and countries created the perfect environment for sharing experiences in order to reach the below perspectives. A full description of the workshop can be found in Chernov et al. (2024).

3 Barriers to using citizen science water quality monitoring for SDG 6 reporting

This section presents the barriers faced in addition to those that are already well-described in the literature relating to reliability, precision and accuracy that lead to general "acceptance" and "usability" issues. In Figure 1 we summarize these barriers.

Awareness of the importance of good ambient water quality was highlighted as an important consideration. Globally, the disparity in access to safely managed drinking water is vast, ranging from over 90 per cent in Europe and North America to 31 per cent in Sub Saharan Africa (World Health Organisation and United Nations Children's Fund, 2021). Furthermore, in 2021 66 countries reported that a proportion of their population relies directly on untreated surface water (rivers, lakes and ponds) for drinking water (World Health Organisation and United Nations Children's Fund, 2021). This reliance on unimproved drinking water sources puts users at direct risk of the pollution and contamination events. In European countries, the perception of risk from water quality issues has been shown to vary according to age, education and engagement with environmental activities (Skuras and Tyllianakis, 2018). In addition Europeans underestimate water use and their dependence on it (Seelen et al., 2019).

To improve awareness, linking climate-related impacts due to changing hydrological patterns with incidents such as the recent Oder River ecological disaster (Free et al., 2023), is important, and work that recognizes that local water quality actions have global climate implications are also welcomed (Downing et al., 2021). Targeted awareness campaigns are also needed to promote public

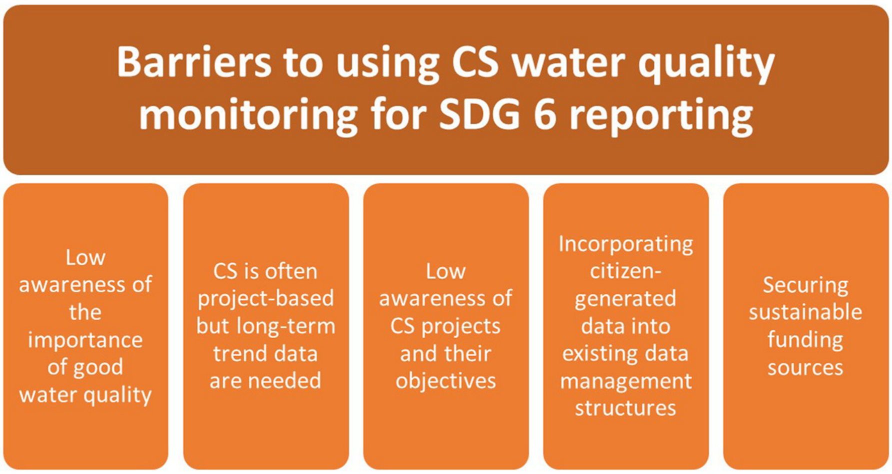

FIGURE 1
Barriers to using citizen science water quality monitoring for SDG 6 reporting.

participation and to awareness across different social strata (Skuras and Tyllianakis, 2018).

Long-term trends need long-term monitoring programs to identify them. Yet long-term and sustainable monitoring requires systems that can endure over time must consider the longevity of equipment, infrastructure, and methodologies employed in data collection to ensure continuous and uninterrupted monitoring. This of course must be embedded in an enabling environment that facilitates such monitoring programs. The challenge for many citizen scientist programs is that they are usually project-based and have a limited life span (Blanco-Ramírez et al., 2023).

Data management of national agencies has been highlighted as a barrier to good water resource management (UNEP, 2021). This hinders access to, and sharing of, data internally and externally within and between organizations, as well as the potential for these data to be properly assessed and made "decision-ready" for decision makers. Incorporating citizen-generated data into existing data management structures has rarely been considered and work is needed to optimize this process that accounts for the known limitations of citizen-generated data (Quinlivan et al., 2020; Hegarty et al., 2021). Moreover, the use and integration of CS data into policy-making process has been identified as a motivational factor for citizens participation (Stepenuck and Genskow, 2018; San Llorente Capdevila et al., 2020).

Securing adequate and stable funding sources is fundamental for sustaining data monitoring initiatives. This is true for national monitoring programs that struggle to maintain regular monitoring activities as well as for citizen scientists. For the latter, costs are presumed to be less than regulatory monitoring but there are questions over the costs involved when all factors are considered (Alfonso et al., 2022). So, more cost-benefit analysis is needed that is broader in scope and accounts for benefits at scales beyond the local environment of the activity. Furthermore, other studies and projects in CS have pointed out the importance of partnerships and funding stability for long-term monitoring and citizens participation (Deutsch and Ruiz-Córdova, 2015; San Llorente Capdevila et al., 2020).

4 Needs from a citizen scientist perspective

This section presents the needs from the perspective of citizen scientists to ensure the data generated can potentially contribute to SDG 6 monitoring. In the Figure 2 we summarize these needs accordingly.

Improving the acceptability of citizen-generated data requires a multifaceted approach that ensures that citizen scientists are suitably engaged and trained to generate reliable data. Training as well as data quality control and assurance protocols are key components of monitoring strategies in CS programs (Stepenuck and Genskow, 2018; San Llorente Capdevila et al., 2020). Continuous capacity building is needed to build technical capacity to apply the chosen methods and going on, to use and navigate through the changing technology. Reskilling and retooling for citizen scientists are essential to ensure they possess the necessary technical skills and knowledge to effectively engage with and adapt to evolving technologies in the field of CS. Empowering citizen scientists with technical capacity enhances their ability to contribute meaningfully to scientific projects, water stewardship initiatives, and advancements. It is essential to foster peer learning and collaboration by creating forums or community spaces where citizen scientists can share their experiences, best practices, and insights regarding the use of technology, and to reinforce sustained motivation action to address water quality issues with multiple stakeholders. In addition, it is essential to provide feedback mechanisms for citizen scientists to share their experiences with the technologies used (San Llorente Capdevila et al., 2020).

Ensuring that the collected data lead to meaningful information is critical. Communication and feedback practices are also considered essential within CS projects (San Llorente Capdevila et al., 2020). This includes the accessibility, comprehensibility, and meaningful interpretation of the data collected by citizen scientists (Cooper et al., 2021). It involves presenting data in a format that can be easily understood and utilized by a diverse audience, including

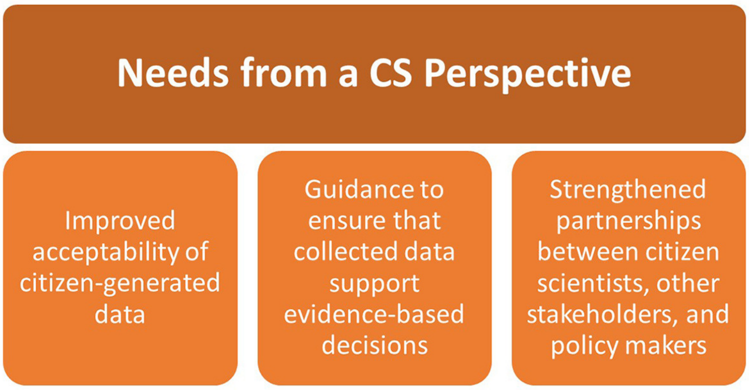

FIGURE 2
Needs of citizen scientists to contribute to water quality monitoring for national and/or SDG 6 reporting.

the public, researchers, policymakers, and other stakeholders. It is essential to produce tutorials, guides, or video demonstrations to enhance data usability by improving users' capabilities to navigate and interpret the data. Moreover, modes of localizing the data to ensure that language barriers do not hinder understanding and usability.

There is a need to mainstream CS into policies. The government, through its agencies, remains responsible for safeguarding the quality of water resources and must work in active partnership with all stakeholders involved in the gathering of data that will lead to more effective decision-making.

5 Discussion

Considering the challenges and the opportunities listed above, this section presents the output of the workshop in terms of what is needed to progress the empowerment of citizen scientists to improve their water quality.

Ultimately, it was identified that a simultaneous bottom-up/top-down approach is needed to ensure that citizen scientist initiatives can generate meaningful and useful data. During the workshop, it was noted that "Locally generated knowledge often has nowhere to go" and therefore data need a destination and purpose, and the information generated must be returned to inform local actions. Going further, "bottom-up" refers to the pressure generated by a growing awareness of the importance of water quality or "the discovery," that leads to the initiation of CS activity and the generation of data. The top-down component refers to the creation or development of a framework that can accept these data and provides a "space" for them to feed into. Whether these CS data are considered in isolation or in combination with national authority data is an important consideration at the project design phase thereby ensuring that the necessary metadata, quality assurance and quality control protocols are available to maximize the potential of the data.

To foster the bottom-up pressure it was acknowledged that local motivated leaders, or a local water quality issue often serve as the "catalyst" and are key to initiate and sustain activities. Going beyond the initiation of activities, promotion of the expansion of CS from small catchment areas to large catchments and ultimately to national, regional, or global scales could promote the concept of "connecting to something bigger." The SDGs offer such a framework to help upscale local activities. Both Sierra Leone and Zambia have incorporated citizen-generated data into their most recent SDG indicator 6.3.2 report to United Nations Environment Programme (UNEP, *pers. comm.,* March 2024). In addition, identifying and showcasing the success stories of CS initiatives, which can be shared through information platforms to reinforce people's awareness and other stakeholders' support would be a useful tool.

The reality that such significant water quality data gaps exist globally (UNEP, 2021), and that national authorities struggle to collect sufficient data, presents an opportunity for citizen scientist-generated data to fill this void. For water quality monitoring, this applies to both spatial and temporal coverage. National agencies are unable to monitor remote locations regularly and are rarely able to collect data at requisite frequencies to gain a good understanding of the natural variation in water quality at a given location. Local citizens are by definition close to the water body, and can collect samples in response to target hydrological conditions such as peak flow conditions, or in response to an observed pollution incident (Quinlivan et al., 2020; Hegarty et al., 2021).

Although many tools and approaches to citizen scientist monitoring exist, it was agreed that promotion of their use and improvements in their accessibility are needed. With advancements in information and communication technology resulting in ever cheaper and more powerful mobile devices, development of low-cost tools for accurately measuring of water variables in real-time should be encouraged.

The development of guidelines or standards to ensure the quality of CS data, to facilitate and enhance their uptake by official authorities would be of value. Bearing in mind the diversity of approaches available, the fitness for use and purpose concepts (Bowser et al., 2020), guidelines on common elements such as quality assurance and quality control, as well as sample collection, and data management protocols would help to build confidence in the data produced (Quinlivan et al., 2020).

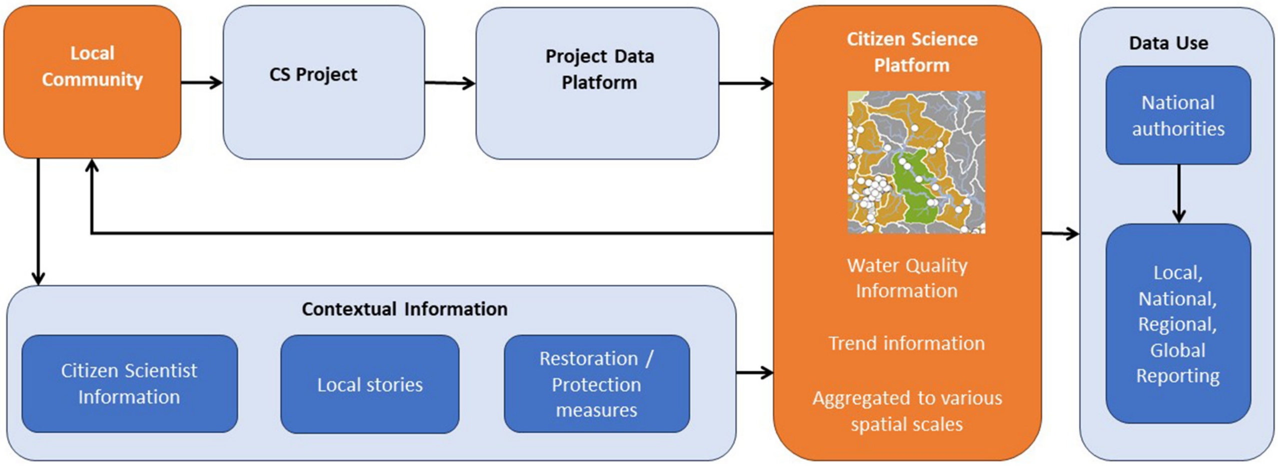

FIGURE 3
Schematic of conceptual "Citizen Science Communication Gateway."

6 Recommendations and way forward

Recommendations that were proposed included most notably developing a communication gateway that allows bi-directional data and information transferal between citizen scientists and civil servants/policy makers (Figure 3). This would include linking citizen data to national, regional, and global reporting such as the SDGs, whilst simultaneously ensuring that information generated from citizen data is returned and contextualized at the local level into meaningful knowledge. Such a gateway could serve as a valuable resource for practitioners, researchers, policymakers, and the wider community, to improve and implement CS initiatives for national regional and global reporting. This platform could host and provide links to case studies, articles, guidelines, and other resources for easy access and reference and thereby serve "to share and showcase the great work out there" as highlighted during the workshop. Moreover, designing of visual infographics, videos, and interactive content is also important to present best practices in an engaging and easily palatable format. Care should be taken not to reinvent the wheel. The gateway should therefore make use of the many different existing platforms.

In addition, it was acknowledged that the following points are important considerations:

1. Collaboration through partnerships is necessary, and through scaling-up and pooling of resources, effective implementation of CS can be achieved. For example, a partnership between academia, local authorities and citizens led to long term positive outcomes in Lebanon (Baalbaki et al., 2019).
2. Further research is needed on participation incentives including different models of citizen participation such as direct payment or additional benefits. Mobile phones serve as useful tools for data collection and validation yet their cost to purchase and airtime can be prohibitve. In Kenya it was found that covering the cost of airtime significantly increases participation in a resource constrained setting (Weeser et al., 2018). Performing a cost-benefit analysis that considers the costs and benefits of citizen engagement in water quality data collection and water resource management to explore the financial, social, and environmental benefits. As highlighted in Alfonso et al. (2022) the cost per measurement for CS data is higher than often expected when factoring in project set up and co-design, but a full cost-benefit analysis as for green/blue infrastructure in Sweden has to date not been undertaken for CS and water resource management (Hamann et al., 2020).
3. The development of diverse funding streams is required that engage with stakeholders, and explore public-private partnerships which are key ingredients to maintain financial stability.
4. It is necessary to enhance the value of data obtained by non-specialized scientists to increase the impact of CS into the research works.
5. Water quality CS data should be verified and validated to ensure they are reliable and accurate before being integrated into the database. As part of the monitoring programme design, building collocated monitoring stations for both national agency and CS monitoring programmes will provide built in validation of data collected. In addition, as highlighted in Tunisia, data fusion techniques can provide confidence in CS data (Jadeja et al., 2018).

It was noted during the workshop that "Potentially, we are all citizen scientists, and actors of change" yet the full potential of CS data for water resource management is yet to be realized. Testing its suitability through processes such as national, regional and/or global reporting frameworks such as for SDG 6, is one path that will help to determine the extent of this potential. Exploring what works and what does not, whilst simultaneously recognizing and accounting for national contexts is essential if acceptance and use of such an approach is to be normalized.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SW: Conceptualization, Investigation, Writing—original draft. SB: Investigation, Writing—review & editing. SV: Investigation, Writing—review & editing. NM: Investigation, Writing—review & editing, Validation. HA: Investigation, Writing—review & editing. CT: Investigation, Writing—review & editing. MI: Investigation, Writing—review & editing. TA: Investigation, Writing—review & editing. EK: Investigation, Writing—review & editing. JC: Investigation, Writing—review & editing. MS: Investigation, Writing—review & editing. AG: Investigation, Writing—review & editing. SL: Conceptualization, Writing—review & editing. MJ: Conceptualization, Writing—review & editing.

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Conflict of interest

JC was employed by Segura.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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