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Citizen science in river monitoring: a systematic literature review of the whys and hows

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River monitoring is a prevalent focus within citizen science projects. Despite numerous reports and institutional manuals detailing the monitoring techniques employed in individual projects, there is a notable lack of comprehensive academic research on the diverse methods and objectives utilized by citizen scientists in river monitoring. This study conducts a systematic literature review to clarify the specific objectives of these citizen science projects and the primary methods used to achieve each objective. We followed the PSALSAR methodology for systematic reviews in environmental science to assess information on global citizen science initiatives in river monitoring available in both published and grey literature. We ultimately reviewed 97 documents from three databases: Web of Science, Google Scholar, and Google. These documents revealed a dominant focus among river-based citizen science projects on objectives related to water quality and river ecosystem health. Methods were varied, and many common methods are routinely applied to multiple objectives. The study provides a framework that links the main objectives to the primary methods, serving as both a practical guide for new initiatives and a valuable index for academic research.

KEYWORDS

stream monitoring, volunteer-based monitoring, participatory science, water quality, community-based, systematic reveiw

1 Introduction

The use of citizen science is well-established in the field of river monitoring (Buytaert et al., 2014), encompassing a wide range of institutions, governmental departments, and community resource groups on a global scale (Conrad and Hilchey, 2011; Njue et al., 2019). Citizen science is characterized by the active involvement of citizen communities in scientific endeavours to support academic research, facilitate information sharing, and encourage public participation in science (Ceccaroni et al., 2017). Citizen science is known to enhance public knowledge, encourage public participation in decision-making, and protect the local natural environment with the information gathered (Walker et al., 2021; van Noordwijk et al., 2021). Numerous studies have demonstrated the reliability of data generated through citizen science, highlighting its effective contribution to diverse facets of river monitoring, including the detection of water quality and monitoring of water levels (Fehri et al., 2020; Njue et al., 2021).

Citizen science is an increasingly important component of river management worldwide. National institutions and NGOs around the globe prioritize river ecology and conservation because rivers play a vital role in being home to flora and fauna, regulating local climates, and providing essential services such as drinking water, irrigation, and recreation for human activities (Milton and Finlayson, 2019). Monitoring is essential for safeguarding natural environments and ecological quality, however governmental and large institutional efforts inevitably fall short in encompassing the entire freshwater system because it is difficult for authorities to cover all tributaries and small water bodies for long-term monitoring (Gurnell et al., 2019). Citizen science projects, organized by communities and local institutions, play a pivotal role in bridging these gaps by providing essential resources for river monitoring data collection, exemplified by large-scale initiatives monitoring for Sustainable Development Goals (Bishop et al., 2020) to regional efforts focusing on microplastic pollution and small waterbodies (Kelly-Quinn et al., 2023).

Professional river monitoring encompasses a variety of methods, including chemical and biological techniques (Pacini et al., 2019; Lamberth and Hughes, 2019), which may be tailored to different monitoring objectives. Many citizen science projects have been developed that either use these methods directly or adapt them to be more user-friendly for volunteers (Simaika et al., 2022). Existing literature on the application of citizen science in rivers primarily focuses on verifying the accuracy and reliance of individual citizen science projects (Krabbenhoft and Kashian, 2020; von Gönner et al., 2023), as well as determining the socioeconomic factors that affect the effectiveness of citizen science projects (Aura et al., 2021; Mgoba and Kabote, 2020). There is surprisingly little information available on how existing citizen science monitoring techniques can be tailored and adapted to meet new monitoring objectives. Without a comprehensive understanding of the common objectives and approaches of citizen science projects, it is difficult to identify opportunities for knowledge sharing, data integration across projects, or opportunities to expand citizen science monitoring as part of national monitoring schemes. It also creates a complex environment for new projects, where a large array of seemingly competing approaches leads to confusion about the best methods to use in any given situation (García et al., 2021).

This study aims to conduct a systematic review of global literature on river monitoring, including academic journals and institutional manuals (grey literature), to identify the principal objectives and monitoring methodologies employed in diverse citizen science projects. The overarching goal is to establish a coherent framework linking objectives with methods for citizen scientists within the realm of river monitoring, outlining cost-effective and operationally feasible methods suitable for citizen scientists. Ultimately, the framework aims to provide foundational guidance for new citizen science initiatives, enabling participants to select appropriate monitoring methods aligned with their conservation objectives effectively. There are three objectives:

a) To identify the primary objectives and monitoring methodologies that are currently being used in existing citizen science projects focused on river monitoring;
b) To explore geographic trends in the objectives and methodologies currently applied in citizen science river monitoring;
c) To synthesize the overarching goals of global citizen science initiatives in river monitoring, categorize the prevalent methodologies associated with each specific goal, and map the most common methods associated with different aims and objectives, thereby providing a decision framework for future citizen science projects in this field.

2 Approach

To perform a systematic search of the literature, we used the PSALSAR method for environmental science research described by Mengist et al. (2020). Existing literature reviews tend to focus exclusively on peer-reviewed literature, which may exclude a large proportion of active citizen science projects (Ramírez et al., 2023). We therefore used Google as well as Web of Science and Google Scholar as our search databases. The search results from Web of Science and Google Scholar primarily consisted of academic journals, while results from Google provided a substantial number of institutional materials. Given the unique nature of citizen science as a source of data from non-academic fields, including grey literature from non-academic sources is essential to capture a broader spectrum of firsthand information on citizen science projects. However, Google searches can also lack specificity, and our search returned an unmanageable number of hits (>16 million). For this reason, we decided to analyse a representative sample of the full dataset by extracting data from only the first 100 search returns. We applied this to all three search databases to ensure parity.

The search terms and screening methodologies utilized across the three databases are detailed in Figure 1. The types of materials included academic evaluations of single or multiple citizen science projects, comparative studies between citizen science projects and authoritative laboratories/monitoring stations, descriptions of monitoring methods suitable for citizen science projects, and research manuals for various citizen science projects.

The search process involved an initial search using the specified search terms in each database. In Web of Science, further categorization using Web of Science Categories was applied. Due to the large number of search results in Google Scholar, additional filtering based on publication date was applied to obtain more recent academic results. The first 100 entries from each database were then manually screened to identify entries that were directly pertinent to specific river-based citizen science projects. 203 papers were excluded at this stage, including institutional manuals informing basic monitoring methods, general reviews on citizen science, specific perspectives on citizen science projects, and projects that did not relate to both citizen science and river monitoring. ‘Specific perspectives’ refer to studies focusing on aspect of citizen science or a citizen science project that is not related to objectives and methods, including papers with a theoretical or critical emphasis. For example, Blake et al. (2020) discusses the demographic composition of citizen scientists and its implication to project effectiveness, and Horvath et al. (2022) demonstrates how citizen science projects can reveal differences in water quality across economic regions.

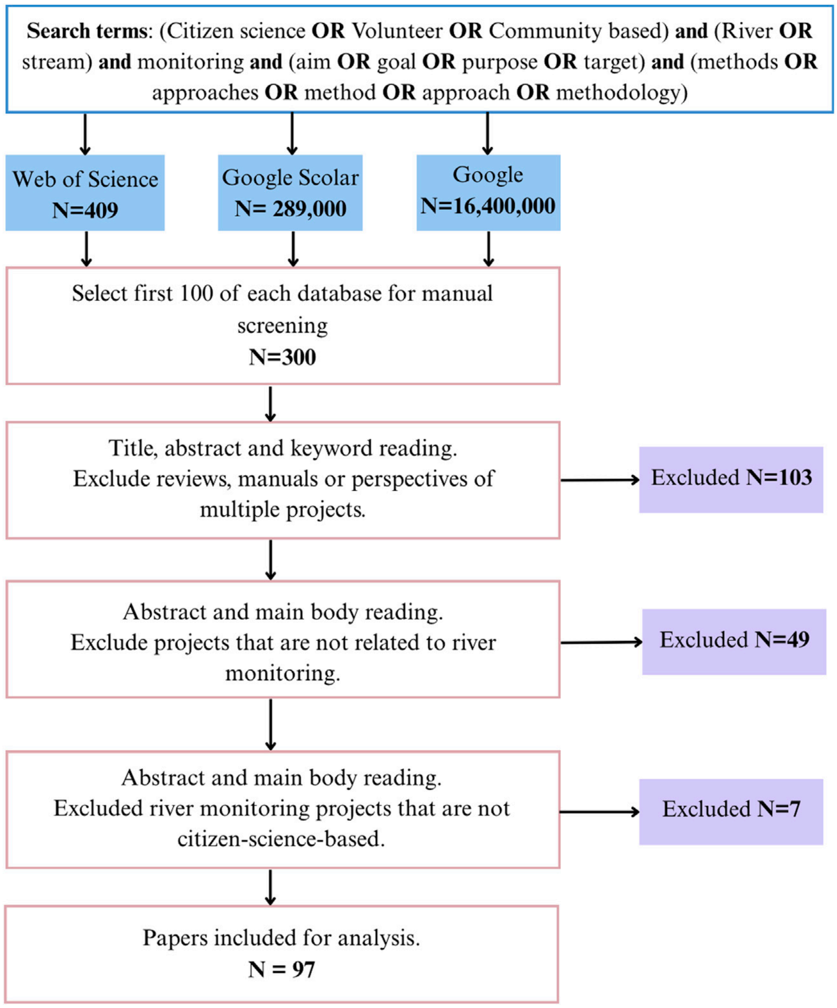

FIGURE 1
PSALSAR flow chart demonstrating literature search and selection process

It is important to recognize the limitations of limiting screening to the first 100 results per platform. In particular, the way in which search engines like Google and Google Scholar rank and display results is influenced by factors beyond keyword relevance, such as citation counts, user search history, and the search engine's commercial algorithms. These factors may bias the visibility of certain sources over others. To mitigate this, the screening process focused on identifying a wide range of study types, geographic regions, and methodological approaches within the 100 results. This included ensuring that both high-profile, frequently cited studies and less-cited or local-scale projects were selected for a more balanced representation of citizen science efforts in river monitoring.

Ultimately, a total of 97 entries from the three databases were selected for subsequent classification and analysis, including 16 studies from Web of Science, 30 studies from Google Scholar, and 34 from Google. According to Figure 2, the majority of these entries were published in the last 10 years, with a smaller proportion (24%) representing older projects dated between 1995–2014. No studies published before 1995 were identified in the search, which may reflect the relatively recent emergence of citizen science projects in the field of river monitoring.

The following information was extracted from each paper included in the review:

1. Research aims and objectives.
2. Monitoring methods deployed.
3. Country of origin of the citizen science project recorded in the paper.
4. Date of publication.
5. Whether the paper consists of citizen-led projects or comparative studies between citizen science projects and authoritative laboratories/monitoring stations.
6. Whether the research methods involve laboratory usage.

Initially, the principal objectives identified in each paper were classified into basic types and further subdivided for detailed analysis. Through a comprehensive review of all 97 selected studies, the objectives of citizen science river monitoring projects were extracted and listed. The monitoring methods associated with each individual objective were documented. Many studies report

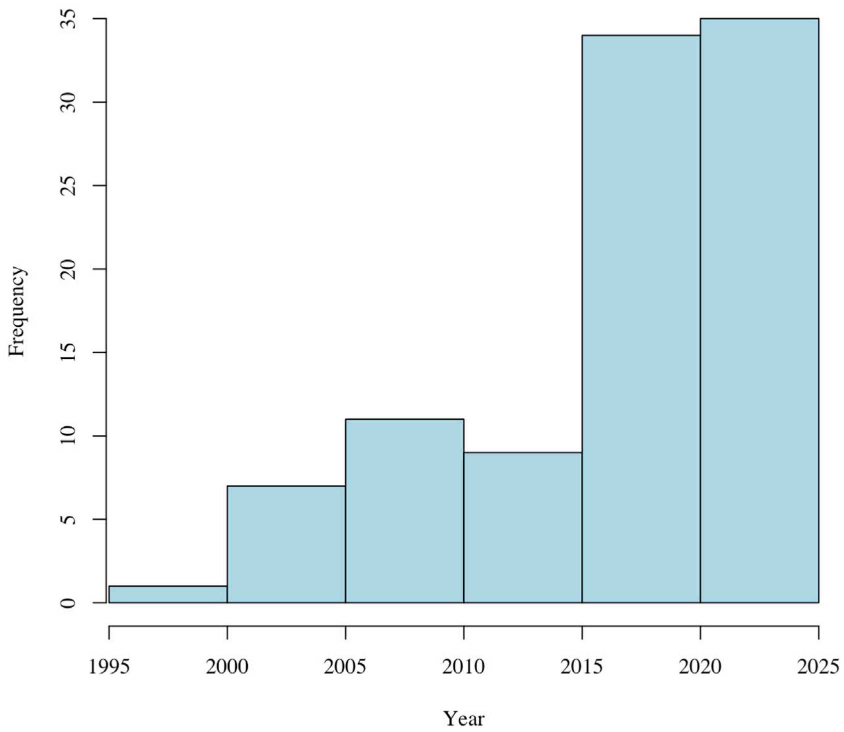

FIGURE 2
Histogram showing publishing year of selected literature.

projects with multiple objectives. For these studies, each objective was documented separately along with the associated research methods employed per objective. This resulted in a total database of 9 different objectives and 7 different methods. Both the objectives and methods were then manually coded according to recurring themes.

An exploratory cross-tabulation was conducted to examine the relationship between the publication year and the geographic location of citizen science projects. However, no clear temporal or regional patterns were observed across the dataset. As such, while publication year and project location were recorded, these variables were not included in the main analysis.

3 Common citizen science objectives

We were able to categorise the objectives of river-based citizen science activities into six groups: 1. protecting ecosystem or river health; 2. assessing water quality; 3. assessing water quality for designated uses; 4. monitoring pollution; 5. acquiring hydrological data; and 6. providing education. Figure 3 shows how these objectives were distributed across the reviewed papers. As we detected studies with more than one objective, all objectives of studies were recorded. Among the 97 recorded studies, 27 have two identified objectives, and 2 have three identified objectives. Therefore, the total of percentages in Figure 3 is 130%, which is higher than 100%.

From Figure 4, the continent with the highest number of selected studies is North America (47), followed by Europe (25), Africa (10), Asia (7), Oceania (5) and South America (1), predominantly reflecting the Global North, although the Global South is also represented. Two studies contain citizen science projects that spread across multiple continents, so they are not recorded under specific continents. The countries with the highest number of selected studies are the United States (37), the United Kingdom (14), and Canada (9).

3.1 Protecting ecosystem or river health

42% of the papers we reviewed had at least one objective focused on protecting ecosystem or river health. This was also the broadest category within our analysis. We further divided the broad category of protecting ecosystem or river health into four sub-categories: protecting habitat or biodiversity, monitoring specific species, assessing impact of human activity, and assessing water quality as an indicator of ecosystem and river health.

Twenty of the objectives within this category were directed towards habitats and biodiversity as key components of overall ecosystem quality. For example, Wilson et al. (2018) exemplify a habitat-focused approach through a citizen science program led by indigenous communities in the Yukon River Basin. The program combines traditional ecological knowledge with scientific data to monitor river health and support biodiversity conservation. By empowering local communities to collect and analyse data on water quality, macroinvertebrate diversity, and fish populations, the initiative aligns citizen

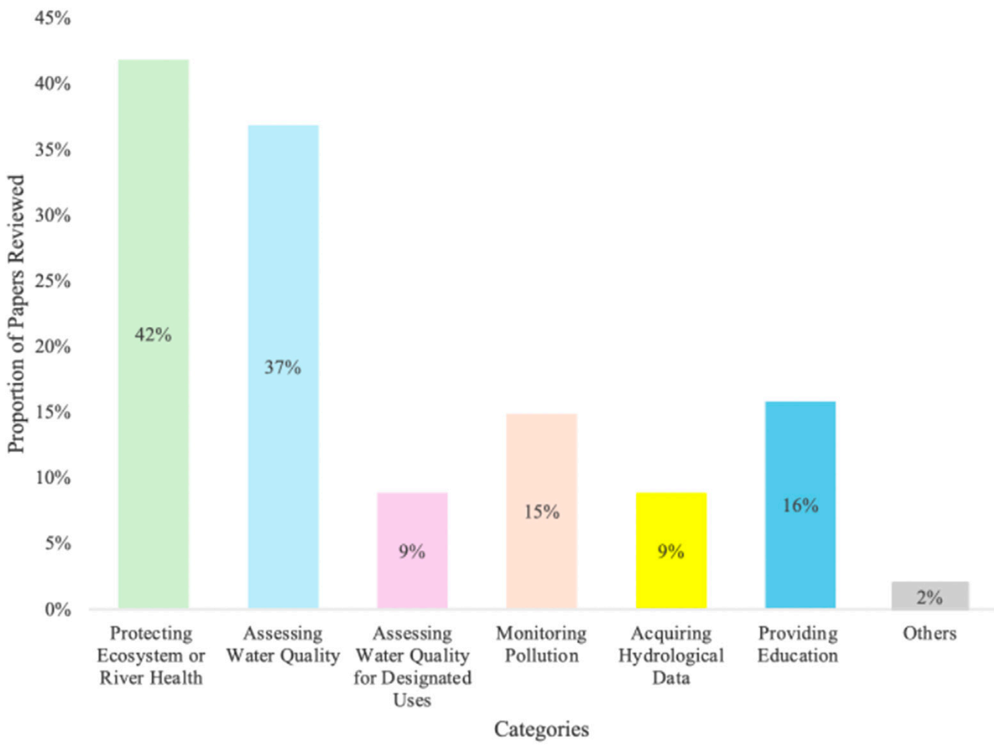

FIGURE 3
Categorization and proportions of objectives.

science with broader environmental stewardship and habitat protection.

In contrast, 5 projects focused on protecting a particular species or group of species, or on observing the activity of specific indicator species to safeguard the broader ecosystem or public health. Dickson et al. (2024) illustrate a species-level focus through the Bellingen Riverwatch program in Australia, which was designed to protect and monitor the endangered Bellinger River snapping turtle (*Myuchelys georgesi*). Volunteers were trained to measure multiple water quality parameters—such as temperature, turbidity, and dissolved oxygen—to identify threats to the species and inform conservation strategies. The project demonstrates how citizen science can address data gaps for endangered species while contributing to ecosystem-level management.

This split between habitats/ecosystems and species-level foci reflects a long-standing tension in conservation between species-level and landscape-level concerns (Franklin, 1993; Olivares-Rojas et al., 2024). Previous reviews on the contributions of citizen science to macroinvertebrate conservation have suggested that species biases could potentially be addressed by adopting a more habitat-focused approach (Deacon et al., 2023). Our analysis reveals that citizen science projects in rivers are already approaching ecological research at different levels of biological organisation and may therefore be less prone to taxonomic bias.

A subset of the objectives (9 projects) within this category focused specifically on monitoring water quality as an indicator of ecosystem and river health. Projects under this category measure various parameters such as chemical, physical, and biological indicators to ensure that the water quality supports a healthy ecosystem. For example, the MiCorps (2024) organises volunteers to monitor the ecological quality of the river by documenting the stream profile, peripheral habitats, riverbank erosion status and water turbidity. This is perhaps indicative of the popularity of water quality methodologies within citizen science, which we will further discuss in Section 4. Another subset of objectives in this category (7 projects) concentrate on evaluating how human activities such as pollution, agriculture, and industrial production affect river ecosystems and environmental quality. These projects monitor changes in the ecosystem caused by anthropogenic factors and aim to mitigate negative impacts, as exampled in Miguel-Chinchilla et al. (2019) measuring turbidity to assess the relationship between urbanization and water quality.

Although all these projects focus on different indicators of ecosystem health, they all have one thing in common: their scientific objectives are associated with a broader intent to protect. maintain, and restore biodiversity and natural habitats. For these types of projects to be successful they must carefully consider their scientific approach, as well as ensuring that the data is correctly interpreted and then acted upon (van Noordwijk et al., 2021).

3.2 Assessing water quality

In addition to the water quality objectives described above, 37% of the identified objectives aim to monitor general river water quality without targeting specific environmental protection or improvement goals. These studies often share common features,

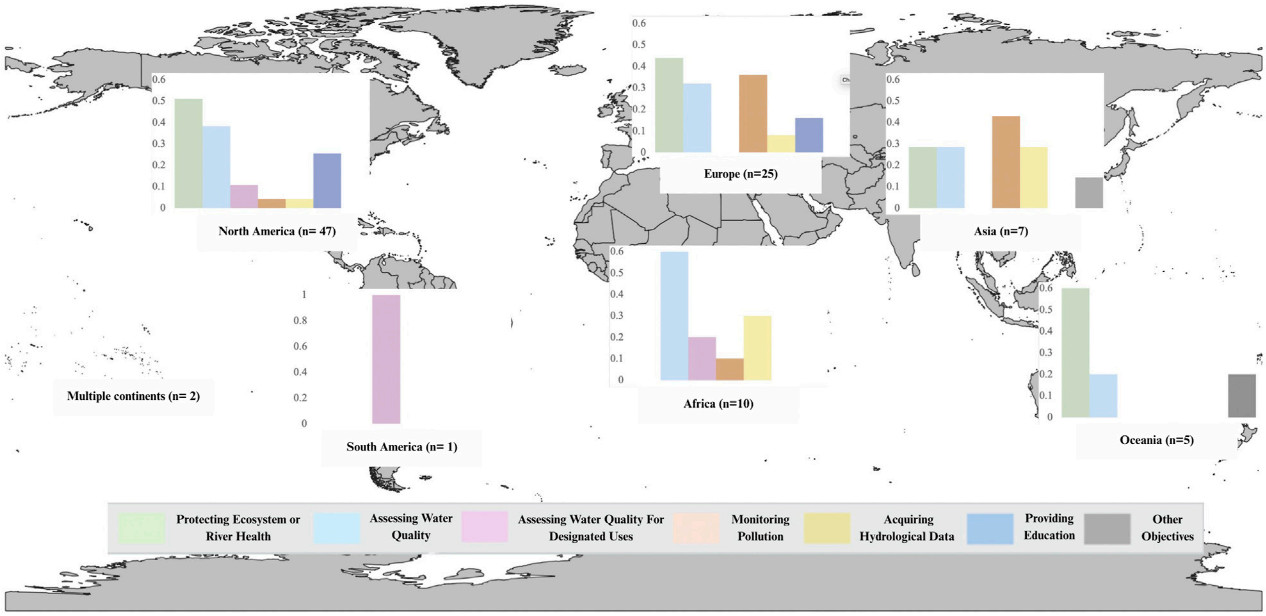

FIGURE 4
Map of origin continent of selected literature.

such as long-term data collection to detect water quality trends and an emphasis on understanding data quality limitations to ensure the effective use of citizen-collected data in official environmental management.

For instance, Nerbonne and Nelson (2008) describe citizen science projects using macroinvertebrates as indicators of water quality. Their findings show that long-term participation and data collection are correlated with improved data utilization. These sustained efforts not only address data gaps but also provide insights into pollution sources related to urban development. Similarly, Hegarty et al. (2021) engaged citizen scientists in monitoring nitrate and phosphate levels in the River Liffey over 9 months. Their study revealed that urban expansion and domestic misconnections contributed to localized pollution.

Several studies compare citizen-collected data with scientifically analysed data, indicating increasing attention to the effectiveness and accuracy of citizen science in the field of environmental monitoring. For example, Njue et al. (2021) compares suspended sediments parameters collected by citizen scientists and automated stations in Sondu-Miriu River basin, Kenya, testing whether citizen-collected water quality data is comparable to expensive professional monitoring; Quinlivan et al. (2020) validates citizen-collected water quality data with professional laboratories to test whether it is able to contribute towards Sustainable Development Goals. This highlights both the potential and challenges of integrating citizen-collected data into formal environmental assessments and decision-making processes. These studies show that while there may be some biases and errors in volunteer-collected data, they can still effectively identify key environmental issues, supporting their integration into decision-making processes: for example, the study results in Njue et al. (2021) shows no significant difference between the citizen science data and automated stations, meaning that citizen science measurement using turbidity tubes provides useful information; Quinlivan et al. (2020) also shows that while citizen science projects showed lower precision in field measurements for nutrients like nitrate and phosphate compared to laboratory assays and greater variability in turbidity assessments than lab-based measurements, most parameters compare well between citizen science data and the accredited laboratory, suggesting its effectiveness in monitoring water quality. This general assessment of water quality is well-aligned with global ambitions to improve our knowledge about the general state of surface water resources and reflects the widespread lack of baseline data that we have on water quality in rivers worldwide (UNEP, 2021). There are calls for citizen science to be more widely adopted to fill gaps in water quality data, particularly with relation to the Sustainable Development Goals (Fraisl et al., 2020; WWQA, 2024), and our findings confirm that citizen science projects that collect this type of data not only exist but are relatively popular, as more than a third of studies reviewed demonstrates river-monitoring citizen science project initiated in order to monitor water quality data.

3.3 Assessing water quality for designated uses

9% of the objectives we identified focused on evaluating river water quality specifically to determine its suitability for various human uses, including drinking water, recreational activities (e.g., swimming, fishing, aesthetics), irrigation, and land use. This objective is closely tied to the daily lives of volunteers, as evidenced by citizen science projects that measure water quality and pollution levels to assess whether the water is safe for consumption or recreational use. For example, Grantz and Haggard (2022) demonstrates the citizen science project StreamSmart, which focuses on collecting long-term data on water chemistry and macroinvertebrates sites in the Upper White

River Basin in the United States to assess land-use impacts. It uses statistical analysis to identify pollution thresholds and improve watershed planning. Middleton (2001) shows how the Stream Doctor Project raises public awareness of water pollution, encouraging citizen participation in monitoring and restoration. It integrates water quality and habitat assessments to identify pollution sources and promote stakeholder-driven watershed management for protecting designated uses like drinking water and aquatic habitats. Babiso et al. (2023) document a project that monitors water quality in the Meki River in Ethiopia, specifically assessing whether its chemical parameters meet the standards for irrigation use. Long-term monitoring is also popular in this objective in order to establish baseline conditions and track changes over time, ensuring data is sufficient for decision-making. Moreover, Community engagement is key as the tested watershed may be linked to communities' daily uses.

3.4 Monitoring pollution

15% of the objectives we identified aim to prevent, monitor, and address pollution issues. These projects focus on various forms of water pollution in rivers, such as nutrient contamination, faecal bacteria pollution, microplastic pollution, and contamination from agrochemical and industrial compounds (Wessex Rivers Trust and Earthwatch, 2024; CESAM, 2024). Additionally, they address pollution in specific wastewater sources and plastic pollution on riverbanks. For example, Graham et al. (2024) introduce citizen science projects in South Africa that specifically address wastewater issues using clarity tubes. These projects also involve interpreting water quality data after collecting them and acting upon it, specifically to mitigate pollution. For example, in the case of Citizen Crane in River Crane, London, volunteers collected and analysed water chemistry and biological data (Cross, 2022). These data were then used by the Environment Agency and the local water company to identify pollution hotspots, target remediation efforts, and report pollution incidents with supporting evidence, leading to concrete interventions, including addressing misconnected outfalls and motorway runoff.

3.5 Acquiring hydrological data

10% of the objectives we identified focus on gathering hydrological data to understand river dynamics and water flow. Given the relative simplicity of the methods associated with collecting hydrological data, only a small proportion of projects include this within their stated objectives. This is particularly surprising given the societal relevance of hydrology (e.g., issues relating to flooding, drought, and water supply) and the fact that hydrology has been identified as a field with large potential contributions from citizen science (Buytaert et al., 2014; Nardi et al., 2022).

3.6 Providing education

17% of the objectives we identified aimed to educate and raise awareness among communities about river health and conservation, as well as methods to monitor and protect water quality. Education programs and activities that run alongside citizen science data collection are commonly designed for students and community members to learn about the water cycle and river ecosystems as part of these projects (Olson, 2023). Again, these objectives cannot feasibly be achieved solely by collecting data. Instead, they rely on the public engagement elements of citizen science to achieve their goals. Learning in citizen science can be achieved in a multitude of ways that encompass both the activities undertaken and the interactions between learners and other participants (Kloetzer et al., 2021). It is therefore no surprise that the themes of projects falling in this category are diverse. For example, Alabama Water Watch emphasizes hands-on environmental education by training volunteers to monitor and protect local water bodies, helping participants develop long-term skills and scientific literacy (Deutsch and Ruiz-Córdova, 2015). Meanwhile, volunteer macroinvertebrate monitoring (Nerbonne and Nelson, 2008) focuses on community-driven restoration, improving stream health through educating the public to change their actions. Other programs, such as school-based monitoring initiatives, engage students with interactive workshops, promoting knowledge of the water cycle and sustainable practices (Overdevest et al., 2004).

4 Commonly used research methods/protocols

We were able to categorise the methods of river-based citizen science activities into seven groups: 1. kick-net sampling or equivalent; 2. chemical and physical measurements; 3. information on the riverbank; 4. monitoring species activities; 5. nutrients; 6. Rainfall, water level or water flow data; 7. bacterial/compound/diatom/DNA experiments. Figure 5 shows how these methods were distributed across the reviewed papers.

Kick-net sampling or equivalent predominantly involves collecting benthic macroinvertebrates by disturbing the riverbed through kicking and using a hand net to take a sweep sample. The collected specimens, which include insect larvae, mollusks, worms, and other phyla, are then identified either on the field or in a laboratory (Marchant and Yule, 2019). Since different species have varying levels of pollution tolerance and inhabit water bodies with distinct chemical, physical and biological conditions, their presence in a particular river area can serve as indicators of the corresponding environmental quality of the river (Tampo et al., 2021). For example, the Save Our Stream project documented in Gowan et al. (2007) uses four metrics based on macroinvertebrates obtained in field samples, to calculate a score indicative of stream health. This method is relatively cost-effective for volunteers and requires less professionality. However, Storey and Wright-Stow (2017) demonstrates that laboratory-examined samples may be more precise compared to those analyzed in the field.

Chemical and physical measurements is the most common methodological category among the 100 selected studies. This method typically includes testing parameters such as water temperature, pH, electrical conductivity, dissolved oxygen, and

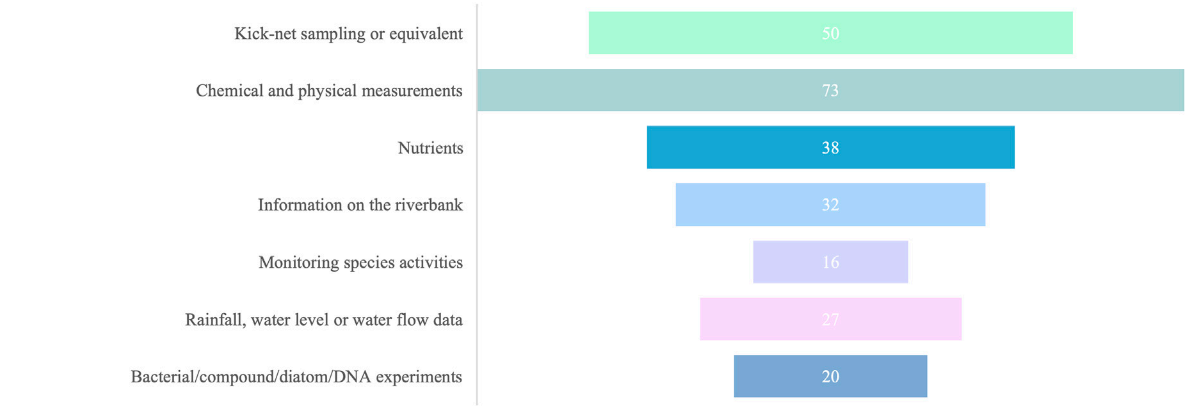

FIGURE 5
Categorization and proportions of methods.

turbidity, and can be conducted using on-field test kits, making it accessible for citizen scientists. For example, turbidity can be measured using Secchi tubes, as demonstrated by Miguel-Chinchilla et al. (2019), while parameters such as pH and conductivity can be tested using specific test kits and strips. These chemical parameters provide citizen scientists with direct indicators and underlying determinants of water quality. However, the preparation of these kits and the maintenance of consistent quality assurance and control are labour-intensive and costly (Savan et al., 2003). Ramírez et al. (2023) have produced a very helpful review of citizen science methods for water chemistry which we do not need to repeat here.

Information on the riverbank is used for general methods including documentation and description of various characteristics in and around the river basin, which could facilitate qualitative analysis of the ecological quality. The index used in studies includes characterization of habitats (Scotti et al., 2022), type of surrounding land use (Edmonson, 2004), height, abundance, structure and species of riverbank vegetation (Modular River Survey Team, 2016). It can also be critical for identifying sources of pollution and monitoring urban interference. For instance, detecting discharge points into the river can indicate potential pollution sources (Miguel-Chinchilla et al., 2019), while counting the presence of livestock, farmlands, and settlements near the river can monitor the level of urban interference (Fore et al., 2001). The MoRPh technique is also used to assess the physical habitat condition of river and the extent of human activities impacting the river area (Gurnell et al., 2019).

Monitoring species activities refers to the observation and recording of species, including their behaviours, quantity, and movements within their habitats. Examples include counting bats to indicate riverine forest quality (López-Bosch et al., 2023), monitoring malaria mosquitoes to assess health risks (Murindahabi et al., 2021), and detecting fish landings to ensure sustainable small-scale fisheries (Silvano and Hallwass, 2020). While these methods enable direct monitoring of species, it is essential for citizen scientists to consider the varying traits of different species and to prioritize health and safety factors during field sampling.

Nutrients can be monitored onsite with test kits by citizen scientists, similar to other chemical measurements. However, nutrient measurement is less commonly performed than parameters like conductivity and dissolved oxygen, possibly due to higher costs. Nutrients primarily affect water quality by causing eutrophication, a form of water pollution characterized by harmful algal blooms that deplete oxygen levels, reduce biodiversity, and degrade water quality (Lintern et al., 2018). In selected projects documented in this study, the commonly measured nutrient parameters include nitrogen, nitrate, phosphorus, phosphate, and chloride (Babiso et al., 2023; Herman-Mercer et al., 2018).

Rainfall, water level or water flow data refers to the acquisition of hydrological data and the dynamics of river water flow. Citizen science projects under this objective often involve monitoring parameters such as water levels and rainfall data, equipping volunteers with tools and techniques, like water level sensor and rain gauges, to systematically collect and record data (Ferede et al., 2022). The parameters are collected to gain hydrological insights, typically involving the use of rain gauges and water level sensors, which demands citizen scientists of equipment installation. For example, river water gauges are used to assess the impact of rainfall on water quality, pollution levels, and habitat conditions (Fehri et al., 2020). Additionally, water flow data is valuable for analysing flow patterns, monitor groundwater recharge, and supports effective river management (Ferede et al., 2022; Weeser et al., 2018).

Bacterial/compound/diatom/DNA experiments represent biochemical experiments conducted to examine the microbiological characteristics of river samples, which detects the presence and concentration of chemical and biological contaminations. It should be noted that this method is not the primary approach for all objectives, but it is utilized in studies addressing the majority of the objectives. The most commonly employed methods include *E. coli* and total coliform tests, exemplified by Burgos et al. (2013) using total coliforms and *E. coli* as parameters to assess water quality. Most of these experiments require professional laboratory facilities, making them less accessible to citizen scientists. However, the establishment of community laboratories has facilitated the

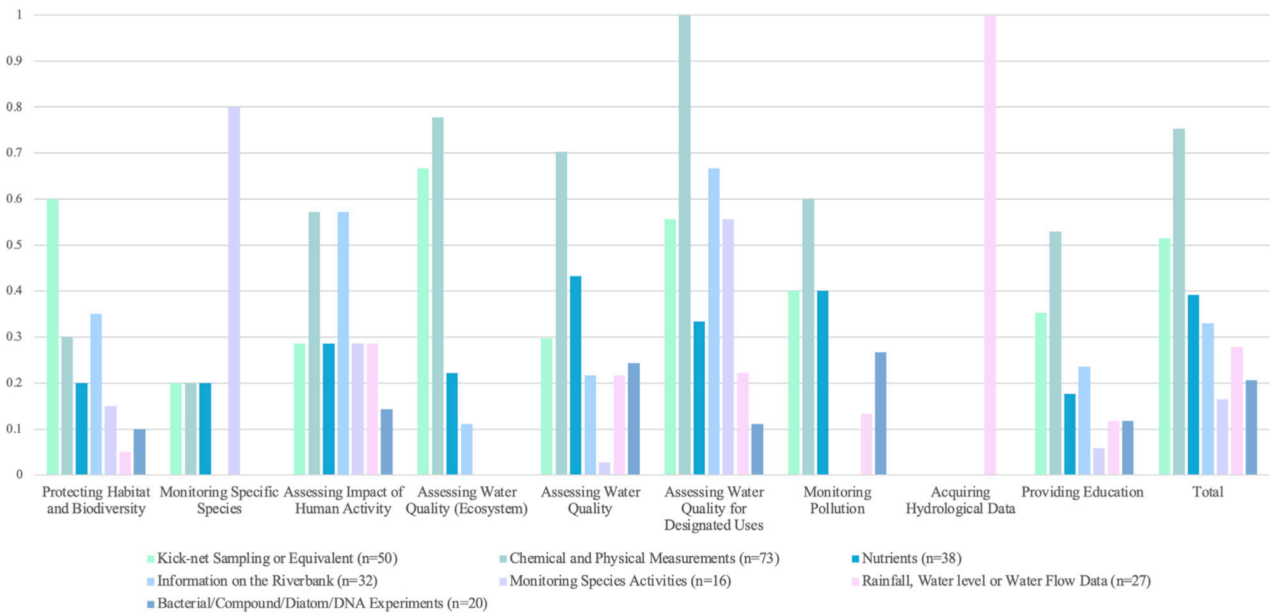

FIGURE 6
Graph of methods used according to objectives *Chemical and physical test includes water temperature, pH, electrical conductivity, dissolved oxygen, turbidity, etc. *Information on the riverbank includes riverbank slope, riverbank vegetation, peripheral land use and human activities, etc.

possibility for citizen science projects to conduct more sophisticated experiments (Water Rangers, 2024).

5 Linking objectives and methods—the framework

Figure 6 represents the proportion of studies using each method across different research objectives. For each objective, bars represent the proportion of studies that employed a given method, calculated based on the total number of studies associated with that objective. As studies often use multiple methods, proportions can exceed 100% when summed across methods. For example, 20 studies fall under the objective of Protecting habitat and biodiversity, and 6 of them used the method of Chemical and physical measurements, the proportion for this Objective-Method is 30%. The proportion metric reflects how commonly each method is used within the context of a specific objective, allowing for comparisons across methods even when studies are not mutually exclusive.

From our literature search, it is evident that most studies employ multiple methods. Generally, kick-net sampling (or equivalent) and chemical and physical measurements are the most commonly used methods, and they are applied across multiple objectives. Conversely, projects under the objective of acquiring hydrological data reportedly only use methods related to acquiring rainfall, water level, or water flow data. Objectives related to monitoring specific species, providing education, and assessing impact of human activities also tend to utilize more specialized methods. For instance, monitoring species activities are primarily used under the objective of monitoring specific species, and assessing impact of human activities primarily uses methods related to information on the riverbank and chemical/physical measurements.

Furthermore, within the broad category of protecting ecosystems or river health, the sub-objective of assessing water quality tends to use fewer but more dominant methods, such as kick-net sampling and chemical and physical measurements. This contrasts with the general objective of assessing water quality, which employs a broader range of methods.

The flowchart in Figure 7 links the common objectives to the primary methods used for each objective. Primary methods of a specific objective are defined as those utilized by more than 40% of the projects under that objective. Each objective draws an arrow to its main methods, illustrating that most objectives employ multiple methods and that most methods are applied across multiple objectives. Generally, the objectives of protecting ecosystem or river health, monitoring pollution, and assessing water quality for designated uses utilize the most methods. Among all methods, chemical and physical measurements, followed by kick-net sampling or equivalent, are the most widely applied. Objectives directly or indirectly aiming to assess water quality—whether through general water quality measurement, designated use assessment, or pollution monitoring—tend to use a greater variety of methods. Conversely, specific objectives such as protecting ecosystem or river health, acquiring hydrological data, and providing education use fewer methods.

In general, kick-net sampling, chemical and physical measurements and gathering information on the riverbank are reportedly more widely used by citizen scientists, requires less training, and costs less, which could indicate their suitability in further citizen science river monitoring projects. Specific methods like monitoring species activities require a particular understanding of the species, and acquiring rainfall, water level,

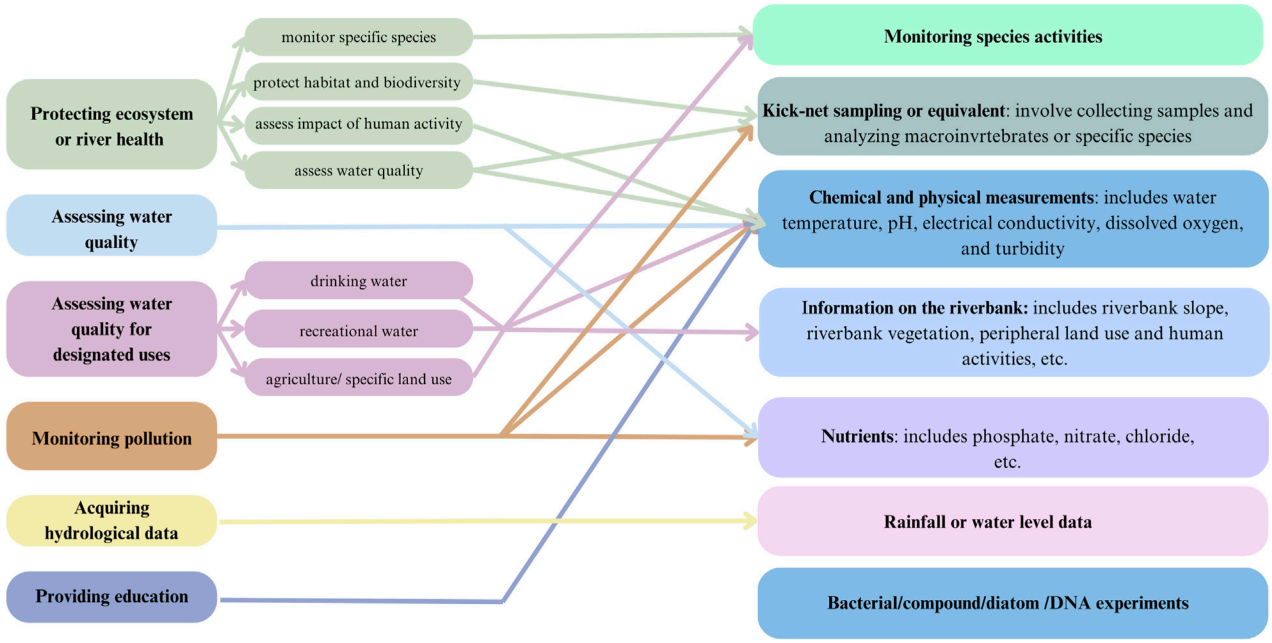

FIGURE 7
A framework linking the objectives to the main methods used.

or water flow data requires the setting of river gauges or sensors, thus they may be limited to specific objectives. The use of bacterial/compound/diatom/DNA experiments requires high cost and professional expertise; it is not a method primarily used in all objectives.

It should be noted that 24% of our documented projects require the use of a laboratory, which may pose obstacles for citizen scientists due to increased requirements for funding, access to resources, and professional assistance. For example, in their evaluation of the Bellingen Riverwatch program, Dickson et al. (2024) note that alongside citizen volunteers, the project operated a complementary professional monitoring stream in which nutrient samples were delivered to an accredited laboratory, with professional scientists providing essential field and laboratory assistance. Similarly, Deutsch and Ruiz-Córdova (2015) reflect on the long-running Alabama Water Watch volunteer network, emphasizing the necessity of rigorous quality assurance protocols, including bacteriological and chemical monitoring, which rely on certified labs and trained staff to uphold standards. Furthermore, the Ilkley Clean River Group's faecal bacteria testing protocol instructs volunteers to collect samples in sterile bottles, keep them between 2°C and 8°C, and arrange analysis by an accredited laboratory, demonstrating the need for coordinated lab partnerships, logistics, and professional support in otherwise community-led monitoring (Ilkley Clean River Group, 2023).

Moreover, sensors, smartphone applications and Geographic Information Systems (GIS) are also commonly used to assess multiple parameters in the water. In this study, all objectives except providing education include projects that use smartphone applications, sensors, or GIS to monitor water quality or water levels. Under the objective of protecting ecosystem or river health, Luchette and Crawford (2008) describe a public-participation GIS platform in the Pamlico-Tar River basin in North Carolina, the United States, where citizens and researchers collaboratively visualized watershed data. Under the objective of assessing water quality, Cârstea et al. (2022) document smartphone-based monitoring along the Danube in Europe, noting that mobile apps allowed volunteers to record water parameters *in situ*, improving data collection frequency and facilitating real-time knowledge transfer across regions. Under the objective of assessing water quality for designated uses, Bannatyne et al. (2017) report on the Tsitsa River in South Africa, where a network of citizen technicians used sensors to monitor suspended sediment, standardizing data collection across the catchment and ensuring consistent sediment measurements. Under the objective of monitoring pollution, Thatoe Nwe Win et al. (2019) introduce a low-cost sensor and smartphone app system for the Ayeyarwady River in Myanmar, where volunteers used handheld sensors and the Akvo Caddisfly app to capture electrical conductivity and turbidity, generating data comparable in quality to professional measurements. Finally, under the objective of acquiring hydrological data, Starkey et al. (2017) introduces the value of GIS-linked community observations for catchment modeling, showing how citizen-collected flow and water level data integrated into catchment-scale models, improving hydrological characterization at a high spatial resolution. The use of these technologies enhances data accuracy and reliability and facilitates the acquisition and documentation of real-time data. However, the associated costs, maintenance requirements, and data management challenges pose significant barriers for citizen scientists (Warner et al., 2024).

This framework acts as a guide that links objectives to methods, providing a clear and intuitive visualization of the linkages between primary objectives and the corresponding methods utilized. By understanding the association between objectives and methods, project organizers can better design their initiatives, ensuring the selection of the most suitable and effective methods to achieve their specific objectives.

6 Conclusion

This systematic literature review offers an assessment of the common objectives and methods employed by citizen scientists in the field of river monitoring. Through a statistical analysis of the global distribution of citizen science projects, we examined their primary objectives and methods used. Our study presents a framework that intuitively links these objectives and methods, providing guidance for new citizen science initiatives in project positioning, objective definition, and efficient method identification. Although this study does not evaluate the effectiveness or efficiency of each method, it offers insight into the frequency and popularity of various approaches, providing a useful reference for selecting methods in future projects. It also categorises, based on all reviewed papers, the main objectives and methods of citizen science projects in the field of river monitoring, with information on their characteristics and examples, which helps identify common practice patterns and supports the strategic design of future initiatives by aligning project goals with suitable methods.

However, the study has certain limitations. To begin with, the literature search is restricted to English language, which likely contributed to the underrepresentation of studies from non-English-speaking regions, such as the very few studies included from South America. Also, the search terms used may not encompass all literature on citizen science projects in river monitoring, and the total of 300 manually screened papers might be insufficient for summarizing general trends in objectives, methods, and their interconnections. Additionally, significant differences may exist between the objectives and methods used in the publications we screened and those in more recent, non-date-limited publications. Furthermore, many citizen science projects may not be documented in the literature, as they may be practiced without being recorded and uploaded to the selected databases. There are also limitations associated with using Google as a source of grey literature, including geographic biases and reproducibility issues related to Google's filtering processes (Paez, 2017). Also, the analysis did not make reference to the temporal and spatial distribution of the reviewed studies. Moreover, 16% of the recorded projects are studies comparing citizen science with professional measurements from laboratories, governmental departments, or monitoring stations. These studies may select different methods than purely independent citizen science projects.

Future research should investigate the development and variation in objectives and methods used in more contemporary river monitoring citizen science projects, for example, with a focus on geographical distribution. Additionally, since the establishment of citizen science projects requires practical training, which cannot be easily conveyed through written frameworks, should focus on delivering practical support. This includes providing technical guidance and hands-on skills training to better equip citizen scientists. Moreover, we look forward to future research that provides systematic evaluations of the effectiveness and efficiency of the various methods described in this study, as well as studies that incorporate theoretical or critical perspectives on citizen science for a more comprehensive analysis.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GS: Writing – review and editing, Writing – original draft. IB: Writing – review and editing, Supervision.

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Conflict of interest

The 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.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. Generative AI was used solely to assist with grammar correction and formatting. The generative AI tool used was ChatGPT (GPT-4, OpenAI, 2024). The content edited using the AI has been reviewed for factual accuracy and checked for plagiarism.

Publisher's note

References

Aura, C. M., Nyamweya, C. S., Owiti, H., Odoli, C., Musa, S., Njiru, J. M., et al. (2021). Citizen science for bio-indication: development of a community-based index of ecosystem integrity for assessing the status of afrotropical riverine ecosystems. *Front. Water* 2, 609215. doi:10.3389/frwa.2020.609215

Babiso, W. Z., Ayano, K. K., Haile, A. T., Keche, D. D., Acharya, K., and Werner, D. (2023). Citizen science for water quality monitoring in the meki river, Ethiopia: quality assurance and comparison with conventional methods. *Water* 15, 238. doi:10.3390/w15020238

Bannatyne, L. J., Rowntree, K. M., Van der Waal, B. W., and Nyamela, N. (2017). Design and implementation of a citizen technician–based suspended sediment monitoring network: lessons from the tsitsa river catchment, South Africa. *Water sa.* 43 (3), 365–377. doi:10.4314/wsa.v43i3.01

Bishop, I. J., Warner, S., van Noordwijk, T. C. G. E., Nyoni, F. C., and Loiselle, S. (2020). Citizen science monitoring for sustainable development goal indicator 6.3.2 in England and Zambia. *Sustainability* 12, 10271. doi:10.3390/su122410271

Blake, C., Rhanor, A., and Pajic, C. (2020). The demographics of citizen science participation and its implications for data quality and environmental justice. *Citiz. Sci. Theory Pract.* 5 (1). doi:10.5334/cstp.320

Burgos, A., Páez, R., Carmona, E., and Rivas, H. (2013). A systems approach to modeling community-based environmental monitoring: a case of participatory water quality monitoring in rural Mexico. *Environ. Monit. Assess.* 185, 10297–10316. doi:10.1007/s10661-013-3333-x

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., et al. (2014). Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Front. Earth Sci.* 2, 26. doi:10.3389/feart.2014.00026

Cârstea, E. M., Popa, C. L., and Donțu, S. I. (2022). Citizen science for the danube river—knowledge transfer, challenges and perspectives. *Low. Danube River Hydro-Environmental Issues Sustain.*, 527–554. doi:10.1007/978-3-031-03865-5_18

Ceccaroni, L., Bowser, A., and Brenton, P. (2017). Civic education and citizen science: definitions, categories, knowledge representation, in analyzing the role of citizen science in modern research. *IGI Glob.*, 1–23. doi:10.4018/978-1-5225-0962-2.ch001

CESAM (2024). Citaqua - a citizen science approach for freshwater quality monitoring at estarreja city. Available online at: https://www.cesam-la.pt/projetos/citaqua-a-citizen-science-approach-for-freshwater-quality-monitoring-at-estarreja-city/[Accessed 18 July 2024].

Conrad, C. C., and Hilchey, K. G. (2011). A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environ. Monit. Assess.* 176, 273–291. doi:10.1007/s10661-010-1582-5

Cross, I. D. (2022). "changing behaviour, changing investment, changing operations": using citizen science to inform the management of an urban river. *Area* 54 (3), 490–500. doi:10.1111/area.12597

Deacon, C., Govender, S., and Samways, M. J. (2023). Overcoming biases and identifying opportunities for citizen science to contribute more to global macroinvertebrate conservation. *Biodivers. Conserv.* 32, 1789–1806. doi:10.1007/s10531-023-02595-x

Deutsch, W. G., and Ruiz-Córdova, S. S. (2015). Trends, challenges, and responses of a 20-year, volunteer water monitoring program in Alabama. *Ecol. Soc.* 20 (3), art14. doi:10.5751/es-07578-200314

Dickson, A., Belmer, N., Denshire, A., Garland, I., Lennox, S., Ruming, S., et al. (2024). Can citizen science inform science? Evaluating the results of the bellingen riverwatch citizen science program and a complimentary government monitoring program. *Front. Environ. Sci.* 11, 1237580. doi:10.3389/fenvs.2023.1237580

Edmonson, C. (2004). The role that volunteer monitoring plays in watershed planning and an evaluation of the USDA stream visual assessment protocol in the booker creek watershed.

Fehri, R., Khlifi, S., and Vancloover, M. (2020). Testing a citizen science water monitoring approach in Tunisia. *Environ. Sci. Policy* 104, 67–72. doi:10.1016/j.envsci.2019.11.009

Ferede, M., Haile, A., Walker, D., Gowing, J., and Parkin, G. (2022). Multi-method groundwater recharge estimation at eshito micro-watershed, rift valley basin in Ethiopia. *Hydrol. Sci. J.* 65, 1596–1605. doi:10.1080/02626667.2020.1762887

Fore, L., Paulsen, K., and O'Laughlin, K. (2001). Assessing the performance of volunteers in monitoring streams. *Freshw. Biol.* 46, 109–123. doi:10.1111/j.1365-2427.2001.00640.x

Fraisl, D., Campbell, J., See, L., Wehn, U., Wardlaw, J., Gold, M., et al. (2020). Mapping citizen science contributions to the UN sustainable development goals. *Sustain. Sci.* 15, 1735–1751. doi:10.1007/s11625-020-00833-7

Franklin, J. F. (1993). Preserving biodiversity: species, ecosystems, or landscapes? *Ecol. Appl.* 3, 202–205. doi:10.2307/1941820

García, F. S., Pelacho, M., Woods, T., Fraisl, D., See, L., Haklay, M. M., et al. (2021). "Finding what you need: a guide to citizen science guidelines," in *The science of citizen science*. Editors K. Vohland, A. Land-Zandstra, L. Ceccaroni, R. Lemmens, J. Perelló, M. Ponti, et al. 419.

Gowan, C., Ruby, M., Knisley, R., and Grimmer, L. (2007). Stream monitoring methods suitable for citizen volunteers working in the coastal plain and lower Piedmont regions of Virginia. *Am. Entomol.* 53, 48–57. doi:10.1093/ae/53.1.48

Graham, P. M., Pattinson, N. B., Lepheana, A. T., and Taylor, R. J. (2024). Clarity tubes as effective citizen science tools for monitoring wastewater treatment works and Rivers. *Integr. Environ. Assess. Manag.* 20, 1463–1472. doi:10.1002/ieam.4937

Grantz, E., Haggard, B. E., and BENG 4973/5973 (2022). Informing volunteer water quality monitoring program design and watershed planning: case study of StreamSmart data analysis in the upper white river basin, Arkansas. *Water Res. Educ.* 177, 46–62. doi:10.1111/j.1936-704x.2022.3380.x

Gurnell, A. M., England, J., Shuker, L., and Wharton, G. (2019). The contribution of citizen science volunteers to river monitoring and management: international and national perspectives and the example of the MoRPh survey. *River Res. Appl.* 35, 1359–1373. doi:10.1002/rra.3483

Hegarty, S., Hayes, A., Regan, F., Bishop, I., and Clinton, R. (2021). Using citizen science to understand river water quality while filling data gaps to meet united nations sustainable development goal 6 objectives. *Sci. Total Environ.* 783, 146953. doi:10.1016/j.scitotenv.2021.146953

Herman-Mercer, N., Antweiler, R., Wilson, N., Mutter, E., Toohey, R., and Schuster, P. (2018). Data quality from a community-based, water-quality monitoring project in the yukon river basin. *Citiz. Sci. Theory Pract.* 3, 1. doi:10.5334/cstp.123

Horvath, I. R., Parolari, A. J., Petrella, S., Stow, C. A., Godwin, C. M., and Maguire, T. J. (2022). Volunteer science data show degraded water quality disproportionately burdens areas of high poverty. *J. Hydrology* 613, 128475. doi:10.1016/j.jhydrol.2022.128475

Ilkley Clean River Group (2023). Protocol: citizen science guide to water testing for faecal bacteria. Ilkley Clean River Group. Available online at: https://ilkleycleanriver.uk/wp-content/uploads/2023/04/Protocol_Citizen-Science-guide-to-water-testing-for-faecal-bacteria-1.pdf.

Kelly-Quinn, M., Biggs, J. N., Brooks, S., Fortuño, P., Hegarty, S., Jones, J. I., et al. (2023). Opportunities, approaches and challenges to the engagement of citizens in filling small water body data gaps. *Hydrobiologia* 850, 3419–3439. doi:10.1007/s10750-022-04973-y

Kloetzer, L., Lorke, J., Roche, J., Golumbic, Y., Winter, S., and Jogeva, A. (2021). "Learning in citizen science," in *The science of citizen science*. Editor K. Vohland (Springer).

Krabbenhoft, C. A., and Kashian, D. R. (2020). Citizen science data are a reliable complement to quantitative ecological assessments in urban Rivers. *Ecol. Indic.* 116, 106476. doi:10.1016/j.ecolind.2020.106476

Lamberth, C., and Hughes, J. M. (2019). "Physical variables in freshwater ecosystems," in *Freshwater ecology and conservation*. Editor J. Hughes (Oxford University Press), 106–132.

Lintern, A., Webb, J. A., Ryu, D., Liu, S., Bende-Michl, U., Waters, D., et al. (2018). Key factors influencing differences in stream water quality across space. *WIREs Water* 5, e1260. doi:10.1002/wat2.1260

López-Bosch, D., Blanch, E., Páramo, F., Flaquer, C., and Lopez-Baucells, A. (2023). What you hear May not be what you see: potential of citizen science methods to use Bats as riverine forest quality indicators. *River Res. Appl.* 40, 92–106. doi:10.1002/rra.4211

Luchette, J. A., and Crawford, T. (2008). A public participation GIS application for citizen-based watershed monitoring in the pamlico-tar river basin, North Carolina. *Southeast. Geogr.* 48 (2), 184–200. doi:10.1353/sgo.0.0022

Marchant, R., and Yule, C. M. (2019). "Aquatic macroinvertebrates," in *Freshwater ecology and conservation*. Editor J. Hughes (Oxford University Press), 240–256.

Mengist, W., Soromessa, T., and Feyisa, G. L. (2020). Method for conducting systematic literature review and meta-analysis for environmental science research. *MethodsX* 7, 100777. doi:10.1016/j.mex.2019.100777

Mgoba, S. A., and Kabote, S. J. (2020). Effectiveness of participatory monitoring and evaluation on achievement of community-based water projects in Tanzania. *Appl. Water Sci.* 10, 200. doi:10.1007/s13201-020-01273-5

MiCorps (2024). Stream monitoring and cleanups. Available online at: https://www.micorps.net/stream-monitoring/(Accessed July 18, 2024).

Middleton, J. V. (2001). The stream doctor project: community-driven stream restoration. *BioScience* 51, 293–298. doi:10.1641/0006-3568(2001)051[0293:tsdpcd]2.0.co;2

Miguel-Chinchilla, L., Heasley, E., Loiselle, S., and Thornhill, I. (2019). Local and landscape influences on turbidity in urban streams: a global approach using citizen scientists. *Freshw. Sci.* 38, 303–320. doi:10.1086/703460

Milton, G. R., and Finlayson, C. M. (2019). "Diversity of freshwater ecosystems and global distributions," in *Freshwater ecology and conservation*. Editor J. Hughes (Oxford University Press), 3–19.

Modular River Survey Team (2016). MoRPhRiver. Available online at: https://modularriversurvey.org/morph-rivers/(Accessed July 18, 2024).

Murindahabi, M. M., Hoseni, A., Vreugdenhil, L. C., van Vliet, A. J. H., Umupfasoni, J., Mutabazi, A., et al. (2021). Citizen science for monitoring the spatial and temporal dynamics of malaria vectors in relation to environmental risk factors in ruhuha, Rwanda. *Malar. J.* 20, 453. doi:10.1186/s12936-021-03989-4

Nardi, F., Cudennec, C., Abrate, T., Allouch, C., Annis, A., Assumpção, T., et al. (2022). Citizens AND HYdrology (CANDHY): conceptualizing a transdisciplinary framework for citizen science addressing hydrological challenges. *Hydrol. Sci. J.* 67, 2534–2551. doi:10.1080/02626667.2020.1849707

Nerbonne, J. F., and Nelson, K. C. (2008). Volunteer macroinvertebrate monitoring: tensions among group goals, data quality, and outcomes. *Environ. Manage.* 42, 470–479. doi:10.1007/s00267-008-9103-9

Njue, N., Gräf, J., Weeser, B., Rufino, M. C., Breuer, L., and Jacobs, S. R. (2021). Monitoring of suspended sediments in a tropical forested landscape with citizen science. *Front. Water* 3, 656770. doi:10.3389/frwa.2021.656770

Njue, N., Kroese, J. S., Gräf, J., Jacobs, S. R., Weeser, B., Breuer, L., et al. (2019). Citizen science in hydrological monitoring and ecosystem services management: state of the art and future prospects. *Sci. Total Environ.* 693, 133531. doi:10.1016/j.scitotenv.2019.07.337

Olivares-Rojas, J., Cook, C. N., and Walsh, J. C. (2024). Synergies of management actions between species and community focused approaches to protecting threatened biodiversity. *Conserv. Sci. Pract.* 6, e13110. doi:10.1111/csp2.13110

Olson, C. M. (2023). *Mixed methods evaluation of a stream monitoring citizen science program*. Oklahoma State University. Doctoral dissertation.

Overdevest, C., Orr, C. H., and Stepenuck, K. (2004). Volunteer stream monitoring and local participation in natural resource issues. *Hum. Ecol. Rev.* 11, 177–185. Available online at: http://www.jstor.org/stable/24707677.

Pacini, N., Pechar, L., and Harper, D. M. (2019). "Chemical determinants of freshwater ecosystem functioning," in *Freshwater ecology and conservation*. Editor J. Hughes (Oxford University Press), 89–102.

Paez, A. (2017). Gray literature: an important resource in systematic reviews. *J. Evidence-Based Med.* 10 (3), 233–240. doi:10.1111/jebm.12266

Quinlivan, L., Chapman, D. V., and Sullivan, T. (2020). Validating citizen science monitoring of ambient water quality for the united nations sustainable development goals. *Sci. Total Environ.* 699, 134255. doi:10.1016/j.scitotenv.2019.134255

Ramírez, B. S., van Meerveld, I., and Seibert, J. (2023). Citizen science approaches for water quality measurements. *Sci. Total Environ.* 897, 165436. doi:10.1016/j.scitotenv.2023.165436

Savan, B., Morgan, A., and Gore, C. (2003). Volunteer environmental monitoring and the role of the universities: the case of citizens' environment watch. *Environ. Manage.* 31, 561–568. doi:10.1007/s00267-002-2897-y

Scotti, A., Marsoner, T., and Vanek, M. (2022). A biodiversity monitoring program for macroinvertebrates inhabiting streams and Rivers of south Tyrol (italy): aims, methodologies, and publicly accessible dataset. *Data Brief.* 45, 108648. doi:10.1016/j.dib.2022.108648

Silvano, R. A. M., and Hallwass, G. (2020). Participatory research with Fishers to improve knowledge on small-scale fisheries in tropical Rivers. *Sustainability* 12, 4487. doi:10.3390/su12114487

Simaika, J. P., Bishop, I., Kelly, M., and Castañeda, R. (2022). "Freshwater biota as indicators of impact: case studies and examples of the major groups in surface water assessment," in *Encyclopedia of inland waters*. Editors T. Mehner, and K. Tockner 2nd edn, Vol. 4 (Elsevier), 20–34.

Starkey, E., Parkin, G., Birkinshaw, S., Large, A., Quinn, P., and Gibson, C. (2017). Demonstrating the value of community-based ('citizen science') observations for catchment modelling and characterisation. *J. Hydrology* 548, 801–817. doi:10.1016/j.jhydrol.2017.03.019

Storey, R. G., and Wright-Stow, A. (2017). Community-based monitoring of New Zealand stream macroinvertebrates: agreement between volunteer and professional assessments and performance of volunteer indices. *N. Z. J. Mar. Freshw. Res.* 51, 60–77. doi:10.1080/00288330.2016.1266674

Tampo, L., Kaboré, I., Alhassan, E. H., Ouéda, A., Bawa, L. M., and Djaneye-Boundjou, G. (2021). Benthic macroinvertebrates as ecological indicators: their sensitivity to the water quality and human disturbances in a tropical river. *Front. Water* 3, 662765. doi:10.3389/frwa.2021.662765

Thatoe Nwe Win, T., Bogaard, T., and van de Giesen, N. (2019). A low-cost water quality monitoring system for the Ayeyarwady river in Myanmar using a participatory approach. *Water* 11 (10), 1984. doi:10.3390/w11101984

UNEP (2021). Progress on ambient water quality. Available online at: https://www.unwater.org/sites/default/files/app/uploads/2021/09/SDG6_Indicator_Report_632_Progress-on-Ambient-Water-Quality_2021_EN.pdf (Accessed July 18, 2024).

van Noordwijk, T., Bishop, I., Staunton-Lamb, S., Oldfield, A., Loiselle, S., Geoghegan, H., et al. (2021). "Creating positive environmental impact through citizen science," in *The science of citizen science*. Editor K. Vohland, (Springer), 373–395.

Von Gönner, J., Bowler, D. E., Gröning, J., Klauer, A. K., Liess, M., Neuer, L., et al. (2023). Citizen science for assessing pesticide impacts in agricultural streams. *Sci. Total Environ.* 857, 159607. doi:10.1016/j.scitotenv.2022.159607

Walker, D. W., Smigaj, M., and Tani, M. (2021). The benefits and negative impacts of citizen science applications to water as experienced by participants and communities. *WIREs Water* 8, e1488. doi:10.1002/wat2.1488

Warner, S., Blanco Ramírez, S., de Vries, S., Marangu, N., Ateba Bessa, H., Toranzo, C., et al. (2024). Empowering citizen scientists to improve water quality: from monitoring to action. *Front. Water* 6, 1367198. doi:10.3389/frwa.2024.1367198

Water Rangers (2024). Community water lab. Available online at: https://waterrangers.com/community-water-lab/(Accessed July 18, 2024).

Weeser, B., Stenfert Kroese, J., Jacobs, S. R., Njue, N., Kemboi, Z., Ran, A., et al. (2018). Citizen science pioneers in Kenya - a crowdsourced approach for hydrological monitoring. *Sci. Total Environ.* 631-632, 1590–1599. doi:10.1016/j.scitotenv.2018.03.130

Wessex Rivers Trust and Earthwatch (2024). Wessex Rivers trust earthwatch microplastics monitoring pilot project. Available online at: https://www.ninevehtrust.org.uk/wp-content/uploads/2021/10/Wessex-Rivers-Trust-Earthwatch-Microplastics-Monitoring-Pilot-Project-min.pdf (Accessed July 18, 2024).

Wilson, N. J., Mutter, E., Inkster, J., and Satterfield, T. (2018). Community-based monitoring as the practice of Indigenous governance: a case study of indigenous-led water quality monitoring in the yukon river basin. *J. Environ. Manage.* 210, 290–298. doi:10.1016/j.jenvman.2018.01.020

WWQA (2024). Technical brief – the role of citizen science in improving ambient water quality. *Tech. Rep.* doi:10.5281/zenodo.12634359