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Citizen science approaches for water quality measurements

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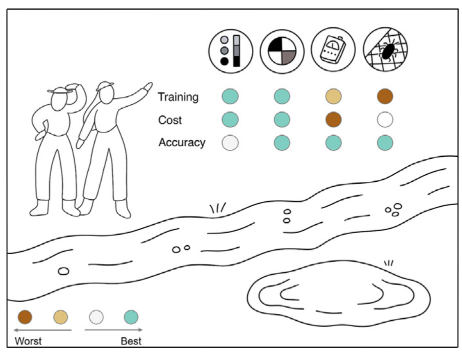
HIGHLIGHTS

- Review of water quality monitoring methods in citizen science projects
- Spatial and temporal resolution of sampling is highly heterogenous.
- Evaluation of methods in term of data accuracy, training, cost, and logistics

GRAPHICAL ABSTRACT



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ABSTRACT

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Contents

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1. Introduction

There is an increasing interest in public participation approaches for hydrological studies and hydrological (water quantity and quality) data collection (Buytaert et al., 2014; Nardi et al., 2021; Njue et al., 2019). The term citizen science is frequently used for this approach, but it includes any 'public participation in scientific research' (Eitzel et al., 2017; Shirk et al., 2012). Several review papers have been written on public participation in hydrologic research and water monitoring in the past decade (Buytaert et al., 2014; Metcalfe et al., 2022; Nardi et al., 2021; Njue et al., 2019; Walker et al., 2020). They mainly focused on data accuracy and data comparison studies (Albus et al., 2019) or the success factors of these initiatives (San Llorente Capdevila et al., 2020). These reviews provide an overview of the state of the art and highlight that in most projects focuses on data collection, and that most water-related citizen science projects focus on water quality (Buytaert et al., 2014; Njue et al., 2019; Walker et al., 2020).

Involving the general public in water quantity and quality monitoring is considered beneficial for different reasons. One of the main reasons is the potential to collect data at larger spatial and temporal scales than is possible with traditional scientific methods (Buytaert et al., 2014; Hadj-Hammou et al., 2017; Hoyer and Canfield, 2021; Lottig et al., 2014; Quinlivan et al., 2020a). Citizen science is also recognized as an opportunity to achieve the monitoring standards needed to reach the sustainable development goals related to water (Bishop et al., 2020; Fritz et al., 2019; Hegarty et al., 2021; Quinlivan et al., 2020b,a). Citizen science can, furthermore, enhance scientific literacy, raise environmental awareness, and build community capacity for environmental protection (Au et al., 2000; Bishop et al., 2020; Kimura and Kinchy, 2016).

Although citizen science in water quantity and quality studies is still relatively new (i.e., it has become part of the peer-reviewed literature only in the last ten years; Njue et al., 2019), public participation in water quality research is much older, especially in the United States (Albus et al., 2019; Hoyer and Canfield, 2021). For example, the Izaak Walton League (1922) was formed by anglers who organized themselves and initiated a water quality assessment of the Mississippi River to protect their rivers (Firehock and West, 1995; Kinchy et al., 2014). The Clean Water Act, a federal policy in the United States established in 1972, encouraged that data collected by the general public was taken into account in the decision-making process regarding water pollution (Deutsch and Ruiz-Córdova, 2015; Field-Juma and Roberts-Lawler, 2021; Stepenuck and Genskow, 2018). Many of the current water quality monitoring networks were established by citizens and non-governmental organizations because of actual water pollution problems. For example, different monitoring networks have emerged around shale gas extraction in Pennsylvania, United States, because of its consequences on water resources (Brasier et al., 2017; Jalbert et al., 2014; Jalbert and Kinchy, 2015; Kinchy et al., 2014, 2016). Community monitoring in Argentina, Peru, Colombia and Ecuador has been driven by the environmental impacts of mining activity, especially their impacts on river water quality (Ulloa et al., 2020; Vázquez, 2019). Elsewhere, studies are addressing the impacts of eutrophication. For example, 400 volunteers collected data over three years on the Huangpu River in China (Zhang et al., 2017) and 600 participants monitored 80 streams and rivers in Brazil (Cunha et al., 2017a,b). Other studies are concerned with water quality for recreational activities (e.g., swimming; Valois et al., 2020). More recently, studies explore citizen science approaches for plastic pollution monitoring, observing macro- and microplastics in freshwater environments (Cook et al., 2021; Forrest et al., 2019; Rech et al., 2015; van Emmerik et al., 2020). The value of the data collected in these studies for community empowerment, strengthening environmental awareness and protection, as well as providing scientific evidence of pollution hotspots cannot be denied (Mccauley, 2017).

The wide range of objectives of citizen-based water quality monitoring projects means that they differ in focus, methods used, and sampling frequency. Some projects have organized monitoring campaigns for several years (Deutsch and Ruiz-Córdova, 2015; Hoyer et al., 2012; Hoyer and Canfield, 2021), others focused on a one-time water quality assessment (e.g., Flores Rojas and Huamantinco Araujo, 2017; Gérin-Lajoie et al., 2018; Quinlivan et al., 2020a). The method used to obtain water quality data does not only depend on the parameter of interest but also on the number of volunteers involved and the budget and duration of the project. This can, in turn, affect the spatial and temporal resolution of the data and its value for different hydrological studies. While, sensors can be used to obtain high-precision and high-accuracy data at a few sites (e.g. 12 community members used a multiparameter water quality meter at three sampling sites (Rivas et al., 2020), one-time sampling campaigns with many volunteers often use cheaper methods that lead to a more extensive spatial coverage but data that has a lower precision (e.g. Muenich et al. (2016) describe a study where 250 participants took physical and chemical measurements using colorimetric test strips at 206 sites). The former is potentially more useful to study changes in water quality over time, while the latter may be more beneficial to determine the spatial pattern in water quality or to find pollution hotspots.

For citizen science projects, it is recommended to keep equipment and sampling procedures simple to allow more people to participate and keep participants motivated (Firehock and West, 1995; Rae et al., 2019; Rambonnet et al., 2019; Walker et al., 2020). Simple methods may also reduce errors (Rose et al., 2016). However, when data are collected following a simplified version of the traditional method, an alternative method, or are not collected by professional scientists, the data are often not trusted and their quality is questioned (Riesch and Potter, 2014). Therefore, the accuracy of citizen science data has received special attention in the scientific literature (Conrad et al., 2011; Jalbert and Kinchy, 2015; Riesch and Potter, 2014). A large fraction of the scientific literature about public participation in water quality monitoring focuses on the accuracy of the data. In most of these studies, the data collected by the public are checked against traditional measurements (Quinlivan et al., 2020b). These studies provide a large and diverse body of evidence that data collected by the public can be accurate and reliable (Albus et al., 2019; Quinlivan et al., 2020b), and that these data can be useful and valuable as a baseline for a general understanding of water quality dynamics (Loperfido et al., 2010; McGoff et al., 2017; Metzger and Lendvay, 2006; Penrose and Call, 1995; Pinto et al., 2020; Shahady and Boniface, 2018; Njue et al., 2021; Xu et al., 2017). However, despite this large body of evidence regarding the quality of citizen science data, there is still a need to determine data quality for large and long-term studies (Albus et al., 2019).

The spatial and temporal distribution of citizen science data has received considerably less attention in the literature than the accuracy of the measurements or "professional vs. citizen" comparisons (McGoff et al., 2017; Millar et al., 2018). However, the spatial and temporal sampling resolution are also important aspects that determine the potential value of the data for further analyses. When and how often the measurements are taken also influences data accuracy or quality, and can be a reason for disagreements between the data collected by citizens and specialists (Hoyer and Canfield, 2021). Thus, this aspect seems equally relevant as the methodology and direct data accuracy assessments. This literature review, therefore, focuses on the different approaches, methods and equipment used within public participation in surface water quality monitoring. The aim is to better understand the different water quality measurement strategies used by citizen science projects and to describe their potential strengths and weaknesses. More specifically, this review looks at water quality related citizen science initiatives from a hydrological perspective to understand how these projects and the collected data can improve the understanding of surface water quality. In other words, we evaluated the sampling strategies, the type of data that are generated and their spatial and temporal resolution, in terms of their strengths and weaknesses for monitoring and scientific water quality studies. This is important because citizen science has the potential to complement existing (national) monitoring programs and can be a source of data in countries where there is a lack of data or limited access to data (e.g. Bishop et al., 2020; Hegarty et al., 2021). More specifically, we addressed the following questions:

1. What measurement approaches are most frequently used in citizen science initiatives for surface water quality monitoring?
2. What are the typical spatial and temporal resolution of the water quality data obtained by citizen science initiatives?
3. What are the advantages and disadvantages of the different approaches used in citizen science initiatives for water quality monitoring? (e.g., potential uncertainties for the different approaches, data accuracy, spatial-temporal resolution, requirement for training and user-friendliness, appeal, and cost).

2. Methodology

To search the literature to be used in this review, we used a systematic review approach. However, we used a traditional literature review approach for the analyses, evaluation and discussion of the studies. We reviewed peer-reviewed papers on citizen science and water quality published before 2022. To search for papers to be included in the review, we used eleven keywords (Table 1) and two academic databases: Web of Science and Scopus. Each database provides different options on subject or research areas; thus, we applied the search filters that we considered most suitable for each database. The search in Scopus was limited to the following subject areas: environmental sciences, social sciences, engineering, agricultural and biological sciences, computer science, and earth and planetary sciences. For the Web of Science search, we selected the following research fields: environmental sciences ecology, public environmental occupational health, water resources, toxicology, science technology other topics, geography, engineering, social sciences other topics, and computer science.

Table 1
List of keywords used in the search for relevant papers and the resulting number of papers in the two databases (Web of Science and Scopus) used in this study. After, excluding duplicates, grey literature, and conference or project reports, this search resulted in 262 unique peer-reviewed papers that were read in more detail.

List of keywords	Number of papers	
	Web of Science	Scopus
"Citizen science" AND "water quality"*	378	239
"Crowdsourcing" AND "water quality"*	40	30
"Collaborative water quality research"	393	220
"Collaborative water quality monitoring"	209	112
"Community-based water quality monitoring"	212	136
"Community-based water quality assessment"	248	118
"Participatory science and water quality monitoring"	83	33
"Participatory water quality monitoring"	151	117
"Volunteer water quality monitoring"	323	115
"Public participation and water quality monitoring"	340	121
"Monitoreo comunitario del agua"	3	2

Citizen science is only one of the terms that are frequently used in peer-reviewed literature. It is related to various terms that refer to the different approaches and levels of participation in which people without a professional, scientific background are involved in scientific research (Eitzel et al., 2017; Shirk et al., 2012; Strasser et al., 2018). Our literature review examines all available peer-reviewed case studies regarding water quality data collection through public participation, regardless of whether citizen science or any other term describing public involvement in a specific task of scientific research is used. We are aware of the importance of recognizing and positioning the concepts used to name a practice, but an epistemological discussion of terms is beyond the scope of this review.

For the papers identified in the first stage, we read the title, abstract, and keywords to select only papers that included the chosen keywords (Table 1). If a paper had these keywords, it was saved in our reference management software (Mendeley). After this keyword search, duplicates, grey literature, and conference or project reports were removed manually from the database. The remaining 262 papers were read in more detail. In this second screening stage, we only selected papers that provided information about the actual public participation in water quality data collection. In other words, we only kept the papers that provided details about the type of data, methods, and the spatial and temporal resolution of the monitoring campaigns (Table 2). Since the interest of this review is on public participation in surface water quality monitoring, studies that focused on water quality in coastal areas, groundwater, or drinking water, water quality management, river or lake water levels, streamflow or rainfall data, and general papers about citizen science and water monitoring were excluded from the analysis. Another 15 studies in which public participation was limited to collecting and shipping water samples for laboratory analysis were also excluded. After this second screening, 72 papers remained in the database (see Appendix for the full list). For each of these papers, we extracted information on the methods used for water quality monitoring, including the temporal resolution and spatial extent of the data collection, and the duration of the monitoring program (Table 2).

Similarly to other literature reviews in the field, the studies indicate a disparity on their geographic distribution (Cunha et al., 2017a,b; Njue et al., 2019; Walker et al., 2020). The majority of the papers reported on projects in North America (48 %), Europe (15 %), and South America (13 %). There were few projects in Asia (13 %), and Australia (8 %). We included a keyword in Spanish (Table 1) to increase the number of studies from South America but only two out of the 72 suitable papers (2 %) were written in Spanish. Only two studies reported on citizen science

Table 2
Overview of the information extracted for each of the 72 reviewed papers and an example for one paper.

Recorded information	Example
Name of the project	Global Water Watch
Reference	Flores-Díaz et al., 2018
Keywords	Title: community-based monitoring, Abstract: water monitoring
Location	Monarch Butterfly Biosphere Reserve, Mexico
Type of waterbody	River
Measured parameters	Chemical and physical
Parameters	Water temperature, hardness, alkalinity, dissolved oxygen, pH and turbidity
Tools/Equipment	Colorimetric/titration kit (Alabama Water Monitoring Kit – LaMotte).
Public participation	Data collection
Training	Training session (These include a regular review of principles and procedures for every test and monitoring session).
Participants	25
Participants profile	Members of civil societies and local inhabitants
Sampling sites	30
Monitoring frequency	Monthly
Duration	5 years
Spatial scale	Catchment
Data transmission	No information
Data quality control	Data Quality Assurance Protocols certified by EPA
Data accuracy	No information

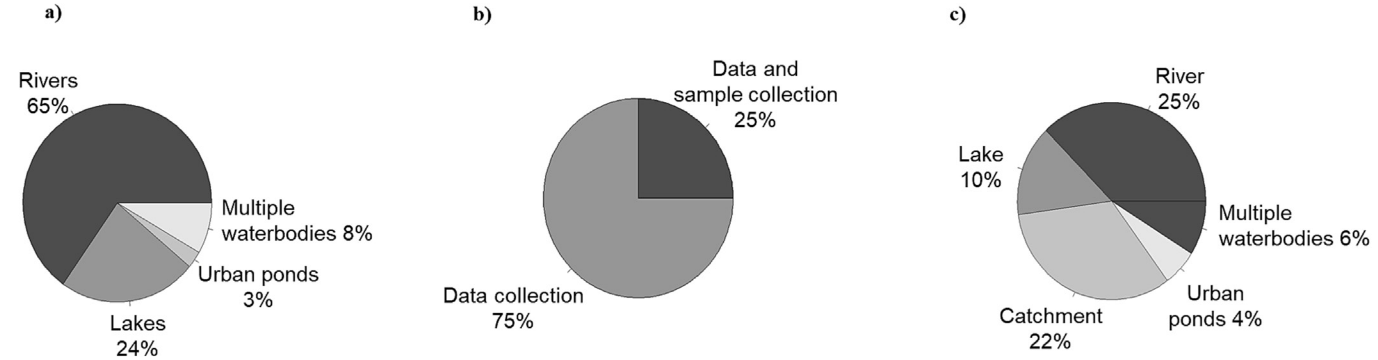

Fig. 1. Proportions of a) waterbodies studied, b) measurement approaches (data collection only, or data collection and sample collection and subsequent shipment to a laboratory, and c) the spatial scale of the reviewed studies.

projects in Africa (3 %). Both projects (Mitroi et al., 2020; Njue et al., 2021) focused on water color and clarity.

3. Results

3.1. Most frequently used approaches for water quality monitoring in citizen science initiatives

Most reviewed studies measured water quality in rivers and streams, followed by lakes. A few studies focused on measurements in multiple waterbodies (e.g., rivers, lakes, and ponds) (Fig. 1a). A quarter of the papers specified that measurements were taken along a particular river or stream, and 22 % of the studies focused at the catchment scale, ranging from 4 km^2 to 13,000 km^2. An almost similar percentage of studies (19 %) focused only on water quality in lakes. Fewer studies (10 %) monitored multiple waterbodies (e.g., urban ponds, streams and lakes) (Fig. 1c). In most of the selected studies, public participation focused on taking measurements directly. However, in some of the studies, participants also collected water samples and shipped them to a laboratory for further analysis (Fig. 1b).

There were different ways that the data were documented and reported in the reviewed studies. Most of the reviewed studies (65 %) did not provide details about this part of the study, but those that did either used paper forms or datasheets (14 %) or smartphone apps (19 %). Some apps are used worldwide (e.g., Fresh Water Watch app), while others were designed or selected according to the study specifications (e.g., Mitroi et al., 2020; Win et al., 2019). A few studies used text messages or postage-paid envelopes to submit the collected data (Sefton et al., 1984; Njue et al., 2021).

As already noted in previous reviews (e.g., Njue et al., 2019; San Llorente Capdevila et al., 2020), most studies did not focus on a single type of water quality parameter but instead covered a variety of parameters, including both chemical and physical aspects of water quality, or a biological water quality assessment. Most frequently, measurements were taken of water clarity, temperature, electrical conductivity, pH, dissolved oxygen, nitrate, phosphate, macroinvertebrates, and fecal coliform bacteria (*E. coli*) (Fig. 2).

The reviewed studies also used different types of equipment for the measurements (Fig. 3). Most of the studies used a colorimetric method (i.e., test strips; 30 %) that gives a concentration range, or titration kits (8 %) that provide more precise concentrations measurements, e.g., in mg/L. Water clarity and turbidity are typically measured using the Secchi tube. For example, the Alabama Water Quality Monitoring Kit used in Alabama and the Global Water Watch campaigns includes alkalinity, hardness,

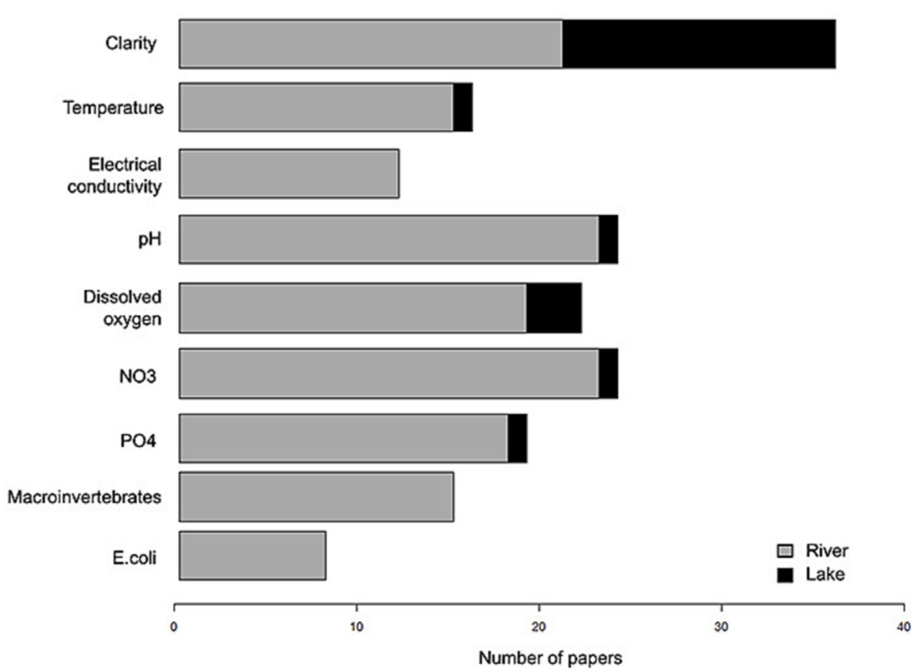

Fig. 2. Frequency of the physical, chemical, and biological water quality parameters measured in rivers and lakes for the reviewed studies. NO3 refers to nitrate concentrations, PO4 to phosphate concentrations, and *E. coli* to the fecal coliform bacteria count.

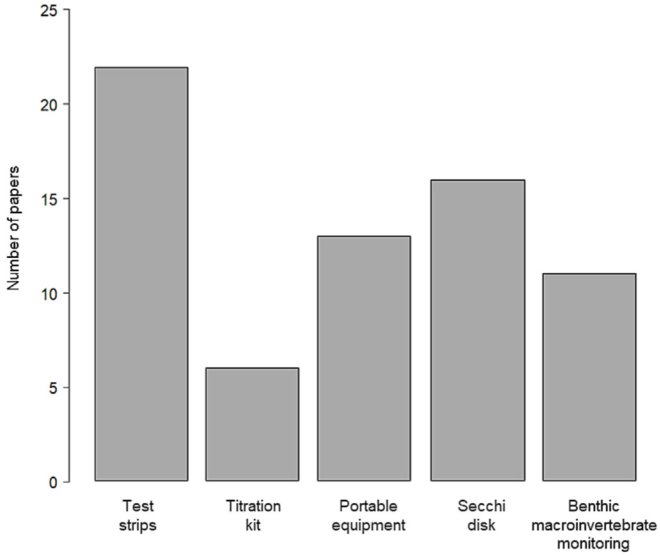

Fig. 3. Equipment and tools used by citizens for water quality monitoring in the reviewed studies.

dissolved oxygen, pH, and turbidity tests. The Fresh Water Watch kit includes test strips for pH, orthophosphate and nitrate measurements, and a calibrated Secchi tube for turbidity observations (14–240 NTU). NIWA's Stream Health Monitoring Assessment Kit (SHMAK) includes tests for visual clarity, temperature, conductivity, nitrate and phosphate concentrations, *E. coli* bacteria count, periphyton, macrophytes and benthic macroinvertebrates. Some test kits are widely used and were mentioned in several of the reviewed papers (e.g. LaMotte Alabama Water Quality Monitoring Kit, the New Zealand Stream Health Monitoring and Assessment Kit, the Kyoritsu PackTest used in the Fresh Water Watch studies or the Hach Nitrate and Nitrite Test Strips or the Alfa water quality test kit).

Portable and more sophisticated equipment has been used in fewer studies (18 % of the papers) (e.g., Hanna pocket pH meter, YSI Model 51B Oxygen Meter, Hach Method - APHA† Method, hand-held Lohand Biological conductivity meter, thermistor, bathyscope, YSI Pro Plus). For example, in the study Quinlivan et al. (2020a), 28 participants measured nitrate and orthophosphate concentrations and chemical oxygen demand (COD) using the Kyoritsu Pack Test and electrical conductivity using a hand-held Lohand Biological conductivity meter for two sites in southwest Ireland.

For benthic macroinvertebrate monitoring, participants used a Surber sampler with a mesh net (aquatic net) to collect benthic macroinvertebrates and afterward help with the taxonomic identification, following simplified guides. In some of the reviewed studies, the participants created taxon abundance and richness metrics (Krabbenhofta and Kashian, 2020; Flores Rojas and Huamantinco Araujo, 2017; Fore et al., 2001; Moffett and Neale, 2015; Shahady and Boniface, 2018) or simple tolerance metrics (e.g., Pinto et al. (2020)).

3.2. Sampling frequency and spatial extent

There is no clear pattern in terms of the spatial and temporal resolution of the measurements in the reviewed studies. The number of sampling sites ranged from one (Flores Rojas and Huamantinco Araujo, 2017) to >1600 (Brooks et al., 2019). The mean and median were 98 and 21, respectively (interquartile range:7–72). Most studies (28 %) had a monthly or twice-per-month measurement frequency (Fig. 4). In one out of eight studies, measurements were taken weekly (12 %; Boylen et al., 2004; Menon et al., 2021; Mitroi et al., 2020; Valois et al., 2020; Win et al., 2019), but there were also studies with only four measurements per year (8 %; Field-Juma and Roberts-Lawler, 2021; Miguel-Chinchilla et al., 2019; Shahady and Boniface, 2018). For 38 % of the papers no measurement frequency was reported.

The objective of 'snapshots' or 'water blitz' events is to collect as many measurements within one day as possible (Flores Rojas and Huamantinco Araujo, 2017; Gérin-Lajoie et al., 2018; Quinlivan et al., 2020a). The number of measurement sites for these types of events reported in the reviewed papers varied from one (Flores-Díaz et al., 2018, where many participants took measurements at the same site) to 206 (Muenich et al., 2016) sites. The median number of sites was 6 (average: 40). Blitzes may occur only once (e.g., Flores Rojas & Huamantinco Araujo, 2002; Quinlivan et al., 2020a) but can also be repeated annually over 10 or 13 years (e.g., Křeček et al., 2018; Moffett and Neale, 2015; Rich, 2019).

The monitoring period for the reviewed studies generally ranged from 1 to 5 years, but some of the reviewed studies took measurements over longer periods, e.g., 10 to 15 years (Arrigo, 2011; Blake and Rhanor, 2020; Brooks et al., 2019; Hoyer and Canfield, 2021; Křeček et al., 2018; Moffett and Neale, 2015; Rich, 2019). For water clarity in lakes, records can be 30 or 70 years long (Bruhn and Soranno, 2005; Canfield et al., 2016; Lottig et al., 2014; Safford and Peters, 2018). For none of the studies in Africa, Asia, or South America was the reported study duration >5 years.

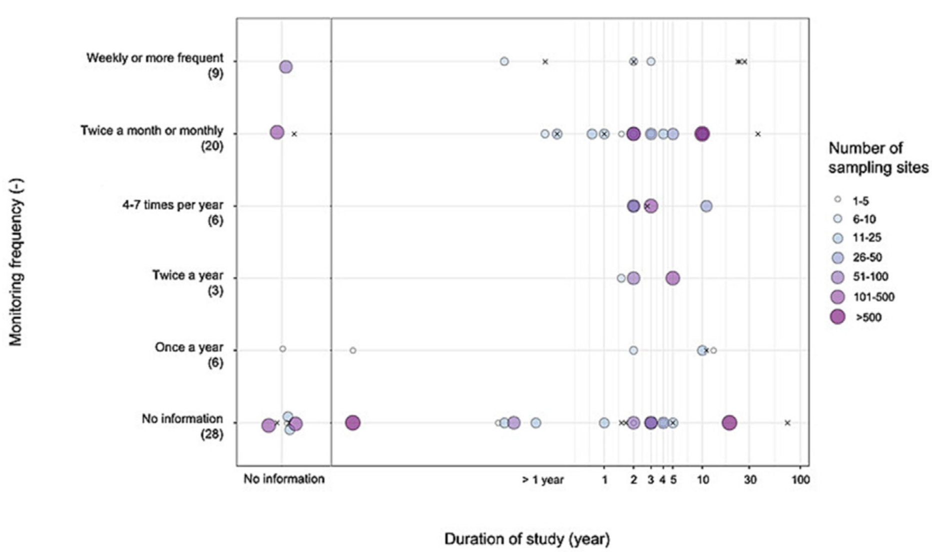

Fig. 4. Monitoring frequency, duration of the monitoring, and the number of sampling sites for the reviewed studies. There is no clear trade-off between the number of sampling sites and sampling frequency or duration of the project. The number given in parentheses below the measurement frequency (y-axis) represents the number of studies. A × is used to represent studies that did not provide information about the number of sampling sites.

For the studies using portable equipment there was a relation between the number of sampling sites and the duration of the project (Spearman rank correlation (r_s) = 0.56) but all projects lasted five years or less. There was also a relation between the number of sampling sites and the duration of the measurements for the benthic macroinvertebrate monitoring (r_s = 0.73). However, there was no overall relation between the monitoring frequency and the study duration (Fig. 4).

3.3. Training and data quality control

Many projects (76 % of all reviewed papers) reported the use of training sessions, where scientists or project leaders explain and show the sampling protocols (San Llorente Capdevila et al., 2020; Stepenuck and Genskow, 2018). These training sessions usually lasted a couple of hours or half a day. Some of these training sessions included field workshops (18 % of all studies, 24 % of all studies with training sessions), while others included written instructions or videos with the kits that were sent to the participants. In some cases (25 % of all studies with training sessions, e.g., the Fresh Water Watch project), participants were required to complete an online training session as part of the recruitment procedure before being able to be involved in the monitoring campaign.

The different data quality control procedures that were implemented included test measurements during the training sessions, supervision during data collection, cross-checked procedures, exclusion of questionable data, audits, or data comparison with lab measurements. For almost half of the reviewed papers (46 %), the data collected by the participants were compared with other data. This comparison included simultaneous measurements at the same sites by scientists or monitoring agencies (e.g. environmental protection agencies) (Fore et al., 2001; Thornhill et al., 2017;Valois et al., 2020; Valois et al., 2019), comparison of the measurements from the kits with laboratory analyses of samples (Lévesque et al., 2017; Quinlivan et al., 2020a; Xu et al., 2017), or comparison with gauge data or remote sensing measurements (Au et al., 2000; Bos et al., 2019; Canfield et al., 2002; Flores Rojas and Huamantinco Araujo, 2017; Fore et al., 2001; Herman-Mercer et al., 2018; Mitroi et al., 2020; Nicholson et al., 2002; Wilson et al., 2018).

4. Discussion

4.1. Evaluation of the different methods

The complexity of a water quality assessment is reflected in the diversity of approaches that were used in the reviewed papers. Selecting an approach is indeed a complex task. Every method has different advantages and disadvantages with regards to cost, logistical efforts, requirements for training, and the type and quality of data that can be obtained (Fig. 5). Developing

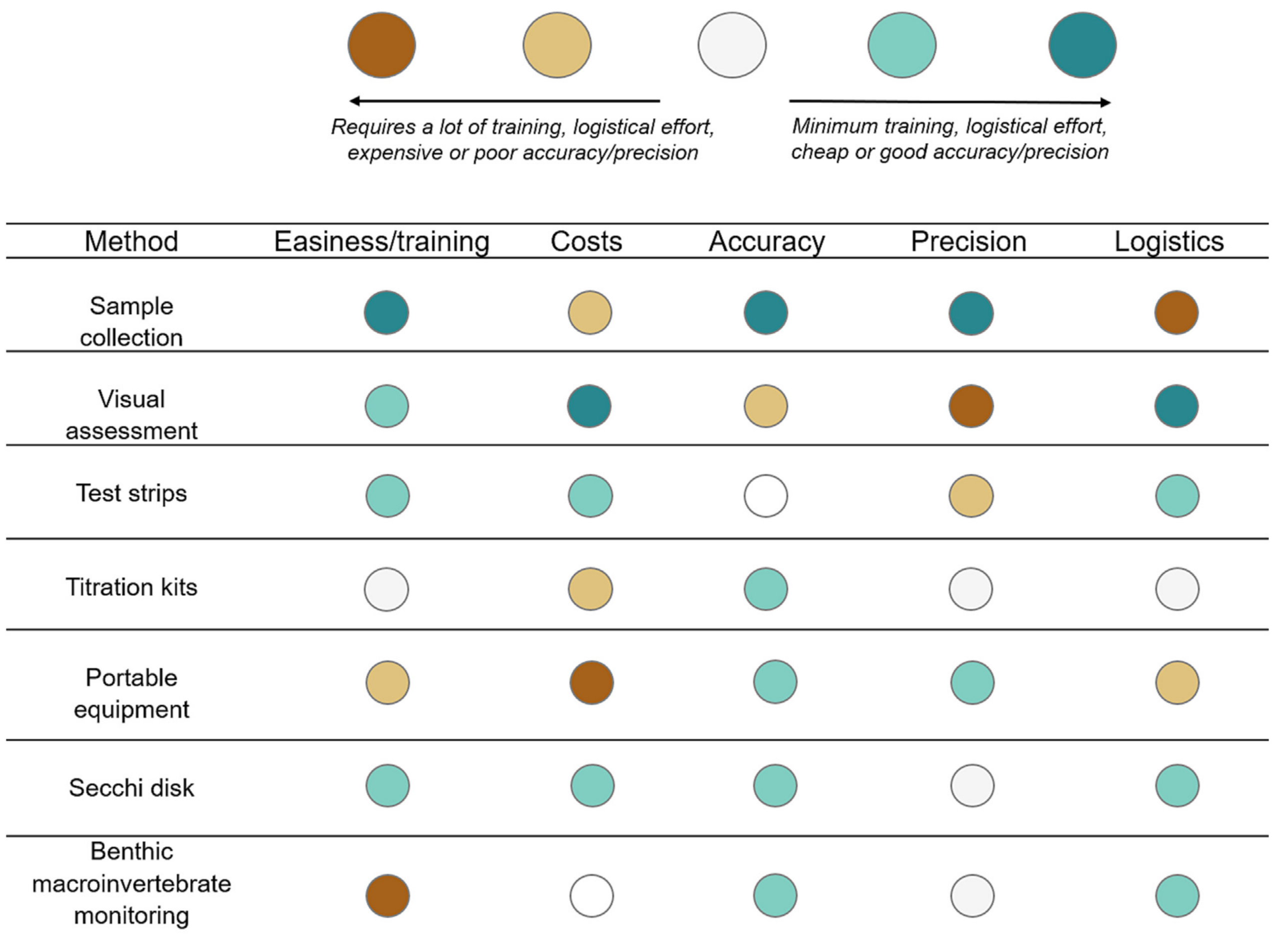

Fig. 5. Strengths and weaknesses of the water quality methods used in the reviewed studies based on our interpretation of the discussion sections of the reviewed papers. The category easiness/training considers if the method requires training as written instructions or a tutorial video (simple), one-two hours training in person, or if requires a half a day training, field workshops or follow up sessions (most difficult). Cost considers the price of the equipment and if the method uses tools that people can get by themselves (e.g. aquatic net or DIY Secchi disk; least expensive), to the price for monitoring kits (ranging from <100–200$) and portable equipment (up to 1000–2000$; most expensive), and logistics includes the effort required in terms of the distribution of equipment, preparation for training, shipment and handling of samples and waste handling, as well as data recording. Accuracy describes how close the measurements are to the true value (i.e., whether the measurements include a bias) and precision refers to the resolution of the measurements or specificity.

a monitoring strategy that provides accuracy but also covers a significant spatial scale to understand spatial variations in water quality and is repeated frequently enough to understand temporal variations in water quality is challenging.

Data quality (accuracy, reliability, and completeness) determines whether a dataset can be used for a specific purpose. In addition to participants' skills, training and sampling protocols, the technology and equipment are key factors that affect data quality (Ali et al., 2019; Quinlivan et al., 2020b). Traditional scientific methods have standardized protocols to ensure that the collected data meets specific standards. The lower precision of the equipment and simpler data quality control procedures used in citizen science projects are some of the main reasons why the scientific community and official monitoring agencies often question or distrust the data from citizen science projects (Hoyer and Canfield, 2021).

Each method has advantages and disadvantages (Fig. 5), which determine the feasibility of obtaining data at a high spatial and temporal resolution, and the accuracy of the data. This, in turn, determines for what types of analyses the data can be used.

Test strips (colorimetric method) are the most frequently used method in the reviewed papers (Fig. 3). The studies in which it was used describe it as a low-cost and easy-to-use method, which makes it particularly attractive for citizen science projects (Fig. 5). A significant difference between colorimetric measurements and measurements with sensors or laboratory analyses is the precision of the data (or sensitivity of the equipment used) (Fig. 5). Colorimetric measurements only provide ranges or classes of concentrations (Jollymore et al., 2017; Quinlivan et al., 2020b; Win et al., 2019). This significantly reduces the usefulness of the data when the differences in concentrations between sampling sites are small, or the variations in concentrations over time are low. In other words, the wide ranges or large classes mean that the measurements cannot be used to monitor small temporal changes in concentrations. There are often also problems with the detection of low concentrations. Typical ranges for nitrate test strips are, for example, five classes between 0.05 and 0.8 mg/L nitrate-nitrogen (SHMAK kit) or six classes between 0.2 to >10 mg/L (Kyoritsu Pack Test kit). Thus, although the colorimetric method is low-cost and easy use for almost anyone, the method is mainly useful to provide a baseline of water quality conditions (Ali et al., 2019; Quinlivan et al., 2020b,a; Win et al., 2019) or to find pollution hotspots (e.g., Thornhill et al., 2017; Ulloa et al., 2020; Zhang et al., 2017). Other factors that affect the reliability of these data include the subjectivity in interpreting and choosing the concentration range by the participants (Quinlivan et al., 2020a). This can be reduced by using tools such as a mobile app, which does an automated reading and interpretation of the test strip's color (e.g., Win et al., 2019). The storage of the test strips may be an important factor that affects its accuracy as well (Win et al., 2019).

Titration kits are also relatively inexpensive and accessible (Fig. 5). Although their precision is slightly better and the data are considered more accurate than for test strips, it has some difficulties in its implementation (Fig. 5). Particularly for dissolved oxygen measurements, Safford and Peters (2018) highlight that the use of these kits requires specific training and knowledge about chemistry, and sample collection and handling as field conditions can affect the sample (e.g., exposing it to atmospheric oxygen, changes in temperature, etc.). The disposal of the chemicals is another challenge.

Although less frequently used, portable equipment or more sophisticated sensors lead to higher precision data (Fig. 5) that can be used to detect changes in water quality. The electrical conductivity sensors maintained by citizens in the study of Inserillo et al. (2017) successfully detected the first flush of solutes in response to tropical storm Sandy. However, the cost and complexity of portable equipment, such as multiparameter sensors, may be a limiting factor in terms of the number (and background) of participants that can contribute to a project, or the number of sites that can be monitored as budgets are often limited (Quinlivan et al., 2020b). In the study by Ho et al. (2020), 250 citizens used a Horiba U-50 Multiparameter Water Quality Meter and a Van Dorn water sampler for two years at seven rivers and streams in Hong Kong. Water temperature, pH, turbidity, and dissolved oxygen were measured and the accuracy of these measurements was compared against the measurements taken by project leaders who used a YSI-6820 multiparameter sonde. The authors highlight that some of the procedures and guidelines were considered very technical, forgotten, or not entirely followed by the participants, leading to some under - or overestimation, especially for dissolved oxygen measurements. Water temperature and conductivity measurements were more comparable to the measurements of the project leaders. For turbidity, there was a better agreement when suspended solid concentrations were lower and participants used the Van Dorn sampler correctly (Ho et al., 2020). Other projects use DIY (do it yourself) sensors based on, for instance, Arduino loggers (e.g. Buytaert et al., 2014). While building these types of sensors is attractive to some people, the time investment to build the sensors and loggers, and to maintain them in outdoor conditions, may prevent widespread use of these types of sensors and thus the spatial resolution of the data.

For benthic macroinvertebrate monitoring, the taxonomic details are simplified and generalized for citizen scientists. Some authors have mentioned that the bias or error is mainly during taxonomic identification (Pinto et al., 2020). Generally, participants identify the aquatic fauna to the family, but not the species, level. Thus, the accuracy of these data is limited to a taxonomic richness assessment, which is helpful as a baseline monitoring, but not to determine specific impacts on water quality (Moffett and Neale, 2015).

Compared to other equipment, the Secchi disks are a low cost and simple tool that can be used at a wide range of spatial and temporal scales (Fig. 5). Secchi disk measurements have been taken by the general public for a long time. The procedures and tools are only slightly different from the measurements taken by scientists (Hoyer and Canfield, 2021; Lottig et al., 2014). Therefore, the accuracy and the quality of the data is more related to skill (or training) than the equipment. For example, Canfield et al. (2016) describe a 37-year dataset of Secchi disk depths at lakes in Maine in the United States. The authors point out that citizen's measurements have a higher precision than Landsat 5 and 7 satellite data and have been valuable to show trends in water transparency and eutrophication. Other studies have shown that with this equipment it is possible to have observations at large spatial scales. Lottig et al. (2014) looked at a 74-year dataset from >3000 lakes across the upper Midwest of the United States and identified long-term patterns at individual lakes and across regional scales.

The review also highlighted the use of qualitative or visual approaches for water quality assessment. The characteristics of the data obtained by these approaches differ from the studies examined in this review and therefore, these studies were not included in the database. However, people have historically paid attention to and described visual aspects (e.g., watercolor, or floating substances) of water quality (Firehock and West, 1995; Mitroi et al., 2020; Valois et al., 2020; Zheng et al., 2017), although these are not numeric or precise observations. People observe and analyze, for instance, turbidity, water clarity or watercolor (Harmsworth et al., 2011; Russell et al., 2020; Stenekes et al., 2020; Zheng et al., 2017), algae growth (Mitroi et al., 2020; Russell et al., 2020; Stenekes et al., 2020), the presence of vegetation or animals (Harmsworth et al., 2011; Russell et al., 2020; Stenekes et al., 2020), floating substances, such as litter and macroplastics (Tasseron et al., 2020; van Emmerik et al., 2020), and the smell of the water (Harmsworth et al., 2011; Townsend et al., 2004; Zheng et al., 2017). Other studies explored cultural (local/traditional/indigenous) knowledge and how this can complement water quality indicators from scientific or western science for water quality assessment (Gérin-Lajoie et al., 2018; Harmsworth et al., 2011; Russell et al., 2020, 2021; Scapini Sobczak et al., 2013). These observations are mostly based on human perceptions and lived experiences, such as visual assessments of water quality indicators (e.g., the water color, presence of algae, smell), and may integrate observations and knowledge to complement scientific measurements and can be useful for environmental management and policy making as well (Russell et al., 2021).

4.2. Spatial and temporal resolution of citizen science water quality data

To understand the quality of citizen science data and its possibilities and limitations, it is important to consider not only its accuracy and precision but also the spatial and temporal resolution of the data. One of our main findings is that there is a lack of discussion on how the monitoring strategies especially the spatial and temporal distribution and extent of the sampling, affects the value of the data for different purposes.

The spatial and temporal resolution of the data and the duration of the collected dataset affect how the data can be used. For example, Rich (2019) reports annual Secchi depth observations at 35 sampling sites for 13 years. This time period can potentially be sufficient to see trends due to land use or remediation efforts. Brooks et al. (2019) report biological monitoring at 1600 sampling sites across the United Kingdom over 10 years at a monthly time step, suggesting that it is possible to obtain high spatial resolution data that includes seasonal variations over a long time period. This temporal resolution can be sufficient to see changes in water quality during wet and dry periods, or due to snow melt. The spatial resolution is sufficient to see differences in water quality dynamics between different locations, but it may not be sufficient to detect sources of pollution within a specific catchment. Blitzes or snapshot campaigns with many measurements taken on the same day (e.g., Cunha et al., 2017a,b; Muenich et al., 2016) in a specific catchment may be more useful to detect water quality anomalies or sources of pollution in that catchment. However, if the sampling occurs only once or twice per year or only a few times, these measurements are less useful to detect any changes in water quality, either due to land use change or management, or due to changes in wetness conditions.

The heterogeneity of the waterbodies and the scale of the study area are important aspects of a monitoring strategy as well. For example, Miguel-Chinchilla et al. (2019) showed in their study that the catchment area had a considerably larger influence on turbidity than local site conditions. McGoff et al. (2017) and Loiselle et al. (2016) suggested that the size of the waterbody or the catchment size also impact the observed nutrient dynamics.

Many studies refer to participatory monitoring campaigns as a valuable approach to cover larger spatial or temporal scales than would otherwise be possible and thus to obtain more data. The average number of sampling sites for the reviewed studies where measurements were taken more than twice per year was 96, and the median was 24 (range: 4–1600) (Fig. 4). From a data collection perspective, this average value suggests a potential benefit of public participation in data collection to increase the spatial resolution of the data compared to what is possible for an individual researcher or monitoring agency. However, the idea that citizen science, is a low-cost strategy to cover large spatial or temporal scales is debated. Adapting techniques and protocols, recruiting and training participants and following up on the monitoring all require a significant time commitment. The economic costs and logistic efforts in terms of equipment can also be high and confront the idea that the involvement of the general public is a low-cost strategy to obtain data (Hadj-Hammou et al., 2017; Hegarty et al., 2021; McGoff et al., 2017).

Most of the reviewed papers did not explain how the sampling sites were chosen, but it appears that in many studies, the citizens chose the monitoring sites themselves. This self-selection allows participants to select sites that are accessible to them and reflects the participants' preferences, and in some cases, their motivations to participate (Jollymore et al., 2017). Some studies have shown that participants tend to choose sites close to their homes, but in other cases, the attractiveness of a waterbody also influences this selection (McGoff et al., 2017; Millar et al., 2018). Any form of self-selection may result in a spatial bias (Jollymore et al., 2017; Safford and Peters, 2018; Scott and Frost, 2017). McGoff et al. (2017) evaluated spatial sampling strategies by comparing the results obtained when participants self-select the sites and a stratified random sampling approach by scientists. The measurements were taken across different waterbodies (ponds, lakes, rivers and streams) and participants and scientists all used the same equipment (Kyoritsu Pack Test kit). With self-selection, participants covered fewer land uses (e.g., cities or crops), which led to a spatial bias that reduced the value of the data to understand water quality dynamics (Hegarty et al., 2021; Millar et al., 2018). However, self-selection does not have to be a problem in all cases. Where data are collected to find pollution hotspots, it may be an advantage if participants select the monitoring locations, as they may have some knowledge of the catchment and potential sources of pollution.

Most reviewed papers did not report the monitoring frequency (Fig. 4). Some studies highlighted that participants usually take measurements during the spring or summer (Hadj-Hammou et al., 2017). Thus, there are periods of under-sampling, which raises the question of the potential value of the data, as water quality varies seasonally (e.g., Hadj-Hammou et al., 2017) and during events (e.g., Knapp et al., 2020). However, most of the reviewed papers that reported the monitoring frequency (38 %) obtained data at a monthly or twice per month interval (Fig. 4). This should allow for the detection of seasonal variations in water quality.

In addition to the measurement frequency, the weather conditions during the sampling campaigns are also important. If measurements are only made during sunny days, the effects of rainfall or storm events are not represented in the datasets. For example, Njue et al. (2021) reported that in addition to the accuracy of the equipment, another major limiting factor for the measurements of sediment concentrations was that participants do not go out to measure it during rainfall conditions. However, although unrelated to water quality, Etter et al. (2020) found that citizens report water level variations during both high and low flow conditions. Thus, if it is clear that the subject of interest varies with flow conditions, it is possible to motivate citizens to collect data over a range of conditions if the measurements are not very time consuming. Loiselle et al. (2016) highlights that for nutrient concentrations, an optimal sampling strategy should consider, in addition to the seasonality, also the first flush during rainfall events. Inserillo et al. (2017) (not included in the database because the keywords did not match) showed that with recording equipment (electrical conductivity sensors that were maintained by citizen scientists), such first flushes can be recorded at many different sites.

The project's duration determines whether it is possible to use citizen science data to assess trends in water quality. Most of the reviewed studies recorded data for less than five years. The most notable exception is Lottig et al. (2014), who present a 74 years dataset of Secchi depth observations in lakes. Indeed, water clarity is the aspect for which more long-term datasets are available (e.g., Boylen et al., 2004; Bruhn and Soranno, 2005; Canfield et al., 2016; Lottig et al., 2014; Rich, 2019). However, there are also long-term studies (more than a decade) on macroinvertebrates (Blake and Rhanor, 2020; Moffett and Neale, 2015) and physical-chemical water quality (Albus et al., 2019; Arrigo, 2011; Hoyer and Canfield, 2021; Křeček et al., 2018; Safford and Peters, 2018). Still, most of the reviewed studies cover a period of five years or shorter. One of the reasons for the relatively short duration of the reviewed studies is the requirement for sustained funding. Many projects seem to not last longer than one funding cycle. Furthermore, many projects only started recently and are still ongoing. It is likely that more peer-reviewed papers will be published from these studies in the coming years.

We expected a negative correlation between the number of monitoring locations and the temporal resolution of the data or the duration of the projects based on the assumption that there is a trade-off between the spatial and temporal sampling resolution or length of the project. This was based on the consideration of logistical challenges and costs, which would only allow one to have a high measurement frequency at a small number of locations or to sustain long-term measurements at a small number of locations, but not both. However, we did not find such a correlation (Fig. 4). This highlights the diverse nature of water quality citizen science projects in terms of the number of sampling sites and measurement frequency, and shows that a wide range of measurement methods can be used for citizen science projects.

5. Concluding remarks

This review paper focused on citizen science studies on surface water quality monitoring from a hydrological and data use perspective. The review highlights the high heterogeneity of monitoring approaches in terms of the methods used and the spatial and temporal scales and resolution of the data. The high heterogeneity in the monitoring approaches illustrates the potential to adapt citizen science projects to any socio-economic and environmental context. Contrary to our expectations, we did not find a relation between the spatial or temporal resolution of the data and the equipment that is used in the projects. Although most of the papers reported on studies that lasted between one to five years, the review also shows special cases with long-term datasets (e.g., 37 or 74 years), especially for water clarity.

The method or type of monitoring equipment used and the spatial and temporal resolution of the measurements affect the potential use of the data to understand water quality dynamics. Some equipment may require more training and is more expensive, thus limiting the number of participants and potentially also their background, but have a better accuracy and precision, which makes the data more valuable for some analyses. Other methods are low-cost and more user-friendly, allowing a greater and wider participation, but the data may not be precise enough for all analyses. For example, colorimetric test strips are the most widely used method to measure chemical water quality parameters because they are relatively simple to use and cheap. However, they only provide data for specific concentration ranges, which may limit the use of the data for trend detection or model calibration.

The increasing interest in citizen science for monitoring purposes (e.g., to monitor progress towards the sustainable development goals) requires that we do not only look at citizen science data from a data quality perspective but also assess the advantages and disadvantages of different monitoring strategies in terms of the value of the data for particular hydrological applications (e.g., the detection of pollution hotspots, changes in water quality, or water quality modeling). This includes guidelines on the minimum requirements for the data to be useful for water quality management or research. The heterogeneity of sampling approaches also indicates the need to develop guidelines and protocols to design comparable (but still flexible) citizen science water quality monitoring projects that can provide data that fit water quality monitoring standards (Quinlivan et al., 2020b).

CRediT authorship contribution statement

Sara Blanco Ramírez: Conceptualization, Methodology, Analysis, Writing – original draft, review & editing, Visualization.

Ilja van Meerveld: Conceptualization, Methodology, Writing, review & editing, Supervision.

Jan Seibert: Writing - review & editing.

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Data availability

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

Declaration of competing interest

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