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Review

Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects

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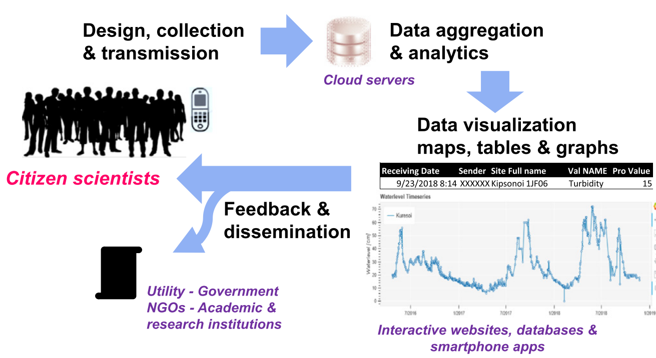
HIGHLIGHTS

- We reviewed applications of citizen science in the context of hydrological science.
- Citizens generate good quality data for hydrological monitoring and modelling.
- Application of citizen science in hydrology is increasing in number and breadth.
- Contributory model is the most common form of citizen science participation.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrological monitoring is essential to guide evidence-based decision making necessary for sustainable water resource management and governance. Limited hydrometric datasets and the pressure on long-term hydrological monitoring networks make it paramount to explore alternative methods for data collection. This is particularly the case for low-income countries, where data scarcity is more pronounced, and where conventional monitoring methods are expensive and logistically challenging. Citizen science in hydrological research has recently gained popularity and crowdsourced monitoring is a promising cost-effective approach for data collection. Citizen science also has the potential to enhance knowledge co-creation and science-based evidence that underpins the governance and management of water resources. This paper provides a comprehensive review on citizen science and crowdsourced data collection within the context of hydrology, based on a synthesis of 71 articles from 2001 to 2018. Application of citizen science in hydrology is increasing in number and breadth, generating a plethora of scientific data. Citizen science approaches differ in scale, scope and degree of citizen involvement. Most of the programs are found in North America and Europe. Participation mostly comprises a contributory citizen science model, which engages citizens in data collection. In order to leverage the full potential of citizen science in knowledge co-generation, future citizen science projects in hydrology could benefit from more co-created types of projects that establish strong ties between research and public engagement, thereby enhancing the long-term sustainability of monitoring networks.

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1. Introduction

Provision of water is one of the most fundamental ecosystem services that underpins the societal wellbeing, which is often a significant bottleneck to sustainable development and poverty alleviation (Buytaert et al., 2014). Despite their importance, catchments in many parts of the world are under severe pressure associated with multiple stressors such as climate change and anthropogenic activities (Everard, 2012; Johnson et al., 2007). These stressors often affect negatively ecosystem health, including hydrological and biogeochemical processes compromising their resilience to cope with extreme events and disturbance (Falcone et al., 2010). Recent studies on environmental land use conflicts provide insights about the hydrological impacts related to the actual land uses that deviate from natural land uses (Araújo Costa et al., 2019; Valera et al., 2016). Development of land ignoring natural capability of soils trigger deterioration of surface water and groundwater quality (Pacheco and Sanches Fernandes, 2016; Valle Junior et al., 2014), change in water flow regimes (Truong et al., 2018), intensification of soil erosion (Pacheco et al., 2014), amplification of flooding (Caldas et al., 2018), decline in freshwater biodiversity and ecosystem services (Valle Junior et al., 2015). Consequently, these hydrological impacts pose significant threats to the sustainable use of water resources (Vanmaercke et al., 2014).

Dense networks for hydrological monitoring with high temporal and spatial resolution are needed to guide evidence-based decision making on sustainable water resources management (Mishra and Coulibaly, 2009; Ochoa-Tocachi et al., 2018). Comprehensive hydrological datasets provide fundamental information necessary to characterize catchment behavior, to make future projections based on models, to implement mitigation measures and to meet policy needs (Tetzlaff et al., 2017). However, long-term hydrological monitoring networks using classical methods (e.g. manual and automatic grab sampling, automatic gauging stations, remote sensing technologies) come at substantial costs associated with installations, management, maintenance and engagement of technical personnel (Buytaert et al., 2014; Lowry and Fienen, 2013; Mazzoleni et al., 2017). Consequently, high costs of implementation often lead to sparse data collection and irregular monitoring. For instance, while remotely sensed data are becoming more readily available, they are still limited by low temporal resolution and involve large uncertainties that make hydrological assessments difficult (Ochoa-Tocachi et al., 2018). Thus, good quality and detailed ground-based observations are required for validation (Starkey et al., 2017). Grab sampling plans are usually too costly for any regional or national monitoring program (Hildebrandt et al., 2006), and sometimes short-lived hydrological events can be missed based on this approach (Jacobs et al., 2018). Fixed monitoring stations and equipment such as river gauging stations and in situ sensors are costly and are susceptible to corrosion, vandalism and theft and therefore require routine site maintenance and security (Gomani et al., 2010; Hannah et al., 2011; van Overloop et al., 2014). Sometimes, the inaccessibility of remote locations limit the amount of data that can be collected with available resources (Zheng et al., 2018). Indeed, recent reviews have noted that hydrological data in many parts of the world are patchy and the lengths of the time series are insufficient to characterize and manage water resources, as many drainage basins remain ungauged or poorly gauged (Chacon-Hurtado et al., 2017; Mishra and Coulibaly, 2009). This implies that areas with limited monitoring networks, particularly the low-income countries, may take longer to attain sustainable water resources management (Buytaert et al., 2014).

There is a growing worldwide need to explore cost-effective data acquisition to generate knowledge for sustainable natural resource management (Buytaert et al., 2016; Loiselle et al., 2016; Pham et al., 2015). This need to develop novel approaches for monitoring environmental data is reflected in the recent growing attention to citizen science. Over the past two decades, citizen science has gained popularity around the world as a promising approach for long-term monitoring of local and global environmental change (Danielsen et al., 2005; Johnson et al., 2014; McKinley et al., 2017; Silvertown, 2009). Citizen science has the potential to enhance knowledge co-creation and science-based evidence that underpins the governance and management of natural resources, complementing conventional ways of monitoring while reducing monitoring costs and significantly improving data coverage, increasing social capital, empowering and supporting decision making (Bonney et al., 2009; Haklay, 2015; Silvertown, 2009). However, criticisms and concerns about the reliability and credibility of data collected have been highlighted as some of the factors impeding the integration of citizen science data into decision making and causing slow acceptance within the scientific community (Catlin-Groves, 2012; Wilson et al., 2018). Consequently, citizen science may not realize its full potential in spite of the growth in open science and an increasing number of scientific projects actively involving citizen scientists (Kullenberg and Kasperowski, 2016; Theobald et al., 2015; Wilson et al., 2018).

Citizen science covers a breadth of fields, having been more prominently and successfully applied in ecology, in biogeography and environmental sciences than in water science (Buytaert et al., 2014; Dickinson et al., 2012). Nevertheless, citizen science is emerging as a viable way to support research in hydrological sciences, especially in monitoring of precipitation, river water quantity and quality, soil moisture levels and flood risk management (Breuer et al., 2015; Loiselle et al., 2016; Lowry and Fienen, 2013; Weeser et al., 2018; Wilson et al., 2018). There are only a few notable examples of these approaches implemented in low-income countries, including Kenya (Weeser et al., 2018), Ethiopia (Walker et al., 2016), Tanzania (Gomani et al., 2010) and South Africa (Kongo et al., 2010), as compared to North America and Europe (Buytaert et al., 2014; Silvertown, 2009). While there is an increasing number of case studies and a growing body of research, a quantitative synthesis assessing emerging trends of citizen science initiatives in the context of hydrological sciences is lacking. Based on this background, this study aimed to provide a comprehensive review on the potential of citizen science and its application in the hydrological context and water resources management. We aimed to answer two research questions: (1) How is citizen science contributing to hydrological research, and (2) What is the future scope of citizen science in hydrology?

1.1. Overview

1.1.1. What is citizen science?

Citizen science is the involvement of the members of the public in different stages within the scientific research process such as collecting, categorizing, transcribing or analyzing scientific data (Bonney et al., 2009). In 2013, the European Commission in their report "Green paper for citizen science" re-defined citizen science as *"general public engagement in scientific research activities where citizens actively contribute to science either with their intellectual effort, or surrounding knowledge, or their tools and resources*" (European Commission, 2013). (Buytaert et al., 2014), described citizen science further as the process where members of the public perform research design, data collection and interpretation, sharing of knowledge and/or analyses alongside professional scientists. Terms such as volunteer-based monitoring (Deutsch and Ruiz-Córdova, 2015), crowdsourcing (Howe, 2006), community-based monitoring (Palmer Fry, 2011), citizen observatories (Liu et al., 2014), participatory sensing (Guo et al., 2014), participatory monitoring (Danielsen et al., 2005), and volunteered geographic monitoring (Elwood et al., 2012), are used to encapsulate many forms of public participation in science. The concept of citizen science varies in area of application, involving implicit or explicit data provision, collecting objective or subjective measurements, from bottom-up to top-down implementation, and using uni- or bi-directional communication paradigms between citizens and data processors (Wehn and Evers, 2015). What is common in all these concepts is the broader vision of involvement of the public in the co-generation of scientific knowledge that provides opportunities for learning and collaboration (Kullenberg and Kasperowski, 2016; Verbrugge et al., 2017). Eitzel et al. (2017) presents a review of the theoretical, historical, geopolitical and disciplinary context of the citizen science terminology.

1.1.2. Early developments

Although it is only recently that citizen science has gained wider recognition, it is not a new concept (Bonney et al., 2009; Silvertown, 2009). Public involvement in scientific discovery has a long history that can be tracked at least to the 19th century and probably earlier (McKinley et al., 2017; Miller-Rushing et al., 2012). The earliest citizen science initiative begun in 1890 with the National Service in the US where volunteers reported daily measurements of air temperature and rainfall (Lee, 1994). The program has over one hundred years of continuous data at 500 stations and with >11,000 volunteers (Pfeffer and Wagenet, 2007). In the early 1900s, the Audubon Christmas Bird count in the US and the British Trust for Ornithology in the UK were founded. These bird surveys are the largest and longest-running successful forms of citizen-science initiatives, currently involving tens of thousands of participants having collected over one million records of species with metadata across the globe (Conrad and Hilchey, 2011; Hochachka et al., 2012; Silvertown, 2009). Since then, the application of citizen science has grown across disciplines, varying widely in terms of scale, size, scope, what is monitored, frequency, level of engagement and costs of monitoring (Danielsen et al., 2005). Citizen scientists participate in a number of research activities including analyzing galaxies (Ponciano et al., 2014), air quality (Snik et al., 2014), invasive species (Gallo and Waitt, 2011), deforestation (Luz et al., 2014), water and soil monitoring (Deutsch et al., 2001), phenology and biodiversity (Fuccillo et al., 2015), and weather monitoring (Reges et al., 2016).

1.1.3. Successful examples

The significant growth of citizen science in natural sciences can be correlated with the increase in technological developments over the past 10–15 years including internet, gamification, robust and cheap sensing equipment, smartphones embedded with web-based mapping tools and global positioning systems (Buytaert et al., 2014; Catlin-Groves, 2012; Khamis et al., 2015). These developments have increased the feasibility of conducting large-scale citizen science projects by streamlining data collection, improving transmission and management of spatial data, automating quality control and expediting feedback communication, even in remote environments (Buytaert et al., 2014; Newman et al., 2012). Limited capacity and scope of monitoring due to decreased agencies budgets in recent decades (Carlson and Cohen, 2018), increasing public knowledge, democratization of science, and concern about anthropogenic impacts on ecosystems (Conrad and Hilchey, 2011), have further driven the need for citizen involvement in environmental monitoring and decision-making. Citizen science models can range from top-down to more bottom-up and participatory approaches depending on the level of engagement (Conrad and Hilchey, 2011; Devictor et al., 2010; McKinley et al., 2012; Paul et al., 2018). Several frameworks exist for assessing the level of engagement in citizen science programs (Bonney et al., 2009; Danielsen et al., 2009; Haklay, 2013; Shirk et al., 2012). The common forms of citizen participation can be categorized into five levels according to the level of influence and involvement in the scientific process, as illustrated in (Fig. 1).

1.2. Citizen science in hydrology

The earliest prototype of citizen science in hydrology is the use of drift bottles in the 1960's and 1970's to study the patterns in surface water currents in the Caribbean sea. The Caribbean Fisheries Development Project released on a monthly basis and for nearly two years thousands of drift bottles in the sea with an enclosed card with instructions for the finder of the bottle to send back the bottle with metadata on the date and place of recovery. The recovery rate was 9.6%, similar to the 7.4% return reported for bottles released off the north coast of Brazil (Brucks, 1971; Luedemann, 1967). These early projects lacked sophisticated platforms by which information was communicated, assembled, integrated and interpreted. Especially, the process of recruiting citizens and waiting for data were elaborate and could take a long time

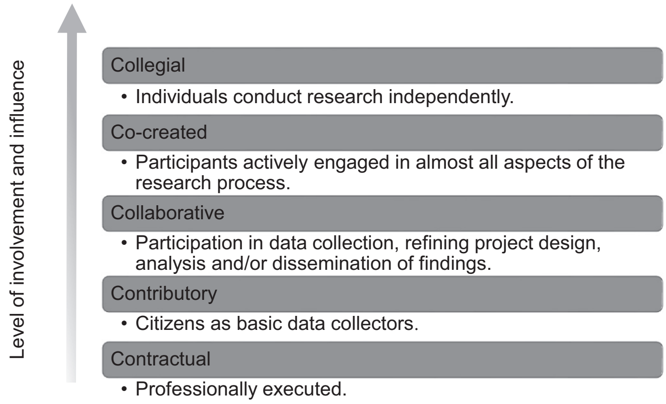

Fig. 1. Typology of citizen science-based program showing levels of involvement and influence. After Bonney et al. (2009) and Shirk et al. (2012).

(Goodchild, 2007). The integration of hydrology within a citizen science framework is often difficult because hydrological measurements are complex, expensive, technologically demanding and require spatially and temporally distributed measurements (Paul et al., 2018).

Current technological improvements of monitoring equipment coupled with Volunteered Geographical Information (VGI) are improving the rate and quality of data collection through location-based, real-time mapping services (Newman et al., 2012), and this is paving the way for faster uptake and applications of citizen science in hydrology (Buytaert et al., 2014; Paul et al., 2018). Several citizen science initiatives for water resource monitoring have emerged worldwide, with networks of well-monitored sites thus improving the spatial coverage of monitoring (Ochoa-Tocachi et al., 2018). Current applications of citizen-led measurements of precipitation, river water quality and quantity, soil moisture, ground water, lakes and oceans offer good examples of citizen science in hydrology. Most of these programs share a collective purpose to promote sustainable water resources management and encourage public participation in the scientific process (Miller-Rushing et al., 2012). These citizen science initiatives are reviewed in this paper.

2. Methodology

In this study we focused on applications of citizen science in monitoring water levels, water quality and/or precipitation as examples in hydrology. To collect information, we reviewed the literature including: peer reviewed articles, book chapters, program websites, and technical reports. Literature was extracted using Google Scholar and Web of Science. Search terms were defined using keywords with synonyms or terms with related meaning (Fig. 2). The Boolean search string method was used to construct search queries. To identify additional relevant articles, we also conducted a backward and forward reference searching examining and reviewing papers cited in the articles selected. Only papers within this scope were considered including: i) Studies that focused on citizen science in a hydrological context and that actively engaged citizen scientists in the scientific research process; ii) Documents published between 2001 and 2018 (both years inclusive), owing to the growth in popularity of citizen science and the emergence of technological developments (Buytaert et al., 2014). Within this period governments, academics, non-governmental and community organizations began to emphasize on the importance of citizen science in environmental monitoring (Jollymore et al., 2017); iii) Papers published in English.

The search yielded 287 articles related to citizen science-based hydrological monitoring. To obtain high-quality sources that matched our objectives and that could help answer our research questions selection criteria were applied, which involved inclusion and quality analysis criteria adopted from the methodology by Talavera et al. (2017). The criteria included:

Abstract check

Papers that did not provide relevant information in their abstracts were discarded at this stage (i.e. only reporting citizen science applications outside the scope of hydrological monitoring). Papers that passed the first criterion were retained.

Full article reading

Papers with minor aspects of our search terms (Fig. 2) in their content were removed even when they contained the terms the abstract. We assessed active involvement of citizens in hydrological research activities, and therefore deliberately excluded studies that employed focus group discussions, questionnaires and surveys of citizens because the citizens involved were the subject of the study and contributed passively.

Quality analysis

Three quality criteria were applied and papers that did not comply were excluded. Studies that used synthetic data to imitate citizen science or others that investigated the potential of citizen science-based technologies for the measurements of hydrological parameters with no clear active involvement or engagement of real citizen scientists were also excluded. However, studies on social media mining that is an emerging trend in this field and serve as a valuable source of data

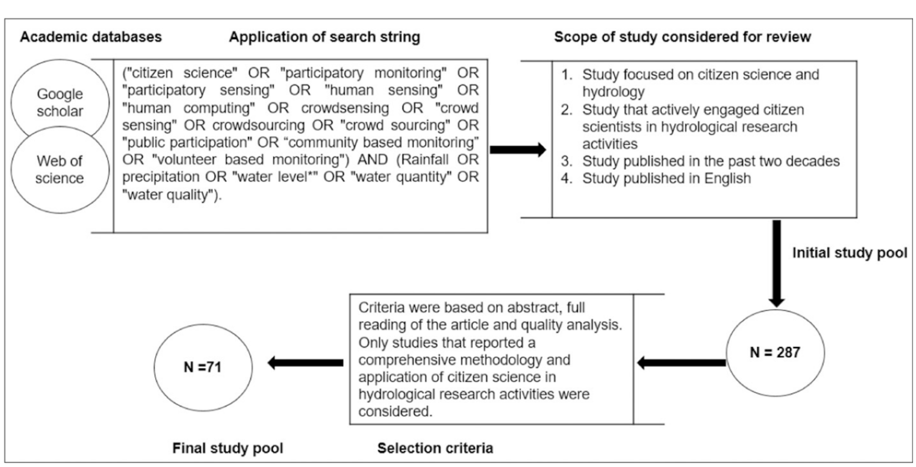

Fig. 2. Overview of review methodology.

of hydrological relevance were included. The assumption was that this approach is participatory in the broader sense, even though participants are usually not aware of their contribution and participation (Michelsen et al., 2016).

The quality analysis was guided by the following questions:

a. Does the study present a comprehensive application of citizen science in hydrological monitoring?
b. Does the study show details of the methodology and technologies used to implement the monitoring?
c. Does the paper present an analysis of the results?

After the iterative search process, 71 papers remained in the pool based on their scientific and technical content. We extracted general information and characteristics of the citizen science approach using a standardized data extraction sheet with predefined research questions (Table 1). We also screened the articles for reporting on opportunities and challenges in applying citizen science in hydrological monitoring.

3. Results and discussion

3.1. Overview of the reviewed articles

The 71 studies reviewed reveal that the number of hydrological-oriented citizen science projects has increased in the last decade (Fig. 3). The number of studies rose rapidly particularly since 2014, coinciding with emerging technologies, low-cost sensing equipment, and a rising interest in sustainable water resource management. The majority of the studies were carried out in high-income regions with North America and Europe being the most represented at 45% and 20%, respectively (Fig. 4). Few studies engaging citizen scientists in hydrology were reported in Australia (4%), and low-income countries in Africa and Asia (10% and 9%, respectively). The uptake of citizen science in hydrology even in low-income countries is gradually rising, although it is still at its infancy. In such countries not only data are scarce, but the pressure on water resources is often already very high and increasing (Buytaert et al., 2016; Hannah et al., 2011). Further characteristics of the reviewed studies are presented in more detail in the Appendix (Table 4).

3.2. Scope of monitoring

Programs ranged in the scope of monitoring from local to global scale. Most citizen science programs (63%) focused on the monitoring of water quality even though water level data are easier to collect than water quality parameters (Fig. 4). This could be due to the increased global awareness of the deterioration of water quality. In addition, there are increasingly more low-cost test kits that measure a wide spectrum of basic water quality parameters, which was also reported by (Buytaert et al., 2014). Programs focused on water quality mostly collect physicochemical (e.g., nitrate, phosphate, turbidity, water color), biological (e.g., macroinvertebrates and *Escherichia coli*) and/or environmental conditions (e.g., land use in the surroundings of the sampling site, presence and number of potential pollution sources, conditions of the riparian vegetation). Some of the programs were limited to the collection of water samples, with subsequent analysis of the samples in the laboratory (Breuer et al., 2015) in comparison to *in situ* measurements of the water quality parameter (Storey et al., 2016).

Table 1
Data extracted from the articles in the final study pool.

- Study reference and year of publication
- Location of the study
- Information on number of study sites/participants and/or measurements
- Time scale of the study
- Monitoring focus
- Training program
- Quality assurance plan
- Communication and data transmission methods
- Form of citizen participation (after Bonney et al., 2009; Shirk et al., 2012)
- Name of the project

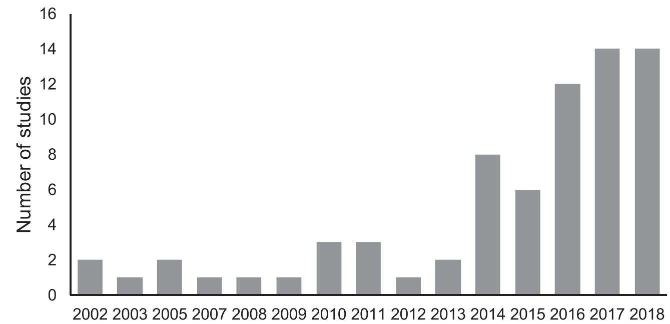

Fig. 3. Citizen science-based studies in hydrological research between 2001 and 2018 (n = 71).

3.3. Spatial and temporal extent

We grouped the spatial coverage and longevity of the programs into three and four categories, respectively (Fig. 5). Spatial coverage varied widely across monitoring networks ranging from single sites spread across a city or country, to entire watersheds, provinces, or states. Of the studies for which the extent of spatial (n = 49) and temporal data (n = 61) could be assessed, most programs (n = 37) monitored <100 sites and only 5 programs monitored >300 sites. One case has a platform that collects data at the global level (EarthEcho, 2015). The time scales for the monitoring period varied considerably ranging from a 1-day observation to >11 years of monitoring. Most studies (n = 32) however, lasted 1–5 years (Fig. 5). Moreover, programs ranged widely in the number of volunteers, with the largest group monitoring thousands of sites.

3.4. Citizen involvement and training

Participation of citizens differed across programs. In some cases, citizen scientists played a central role in designing the research, protection and basic maintenance of monitoring equipment, data or sample collection, data analysis, interpretation and dissemination of results. We classified each study based on the degree of involvement of the participants as described by (Bonney et al., 2009; Shirk et al., 2012). Most of the studies included in our review (73%) were classified as contributory, i.e. the studies were designed by scientists with citizens primarily contributing to data collection or sample collection. Some studies also showed aspects of a collaborative model with citizens engaged also in analyses of the samples or dissemination of results (23%). Only 4% of the studies were classified as co-created projects, employing a deeper citizen involvement including study design, data analysis and interpretation (García and Brown, 2009). Professionally executed (contractual model) and citizen-led approaches in scientific research (collegial model) were not employed in any of the studies. All studies involved citizens in data collection and most programs trained the citizens (82%) and followed various quality control measures (90%) to enhance credibility and quality of citizen science generated data. Burgess et al. (2017) note that best practices for scientific outcomes include attention to training, protocol and materials that prepare participants to effectively collect high quality data. The studies used quality control checks such as simplified data collection protocols, standardized training of participants, replication-based method, using time series analysis or comparing citizen science data with standard methods or expert data for validation and identification of outliers (Jollymore et al., 2017; McGoff

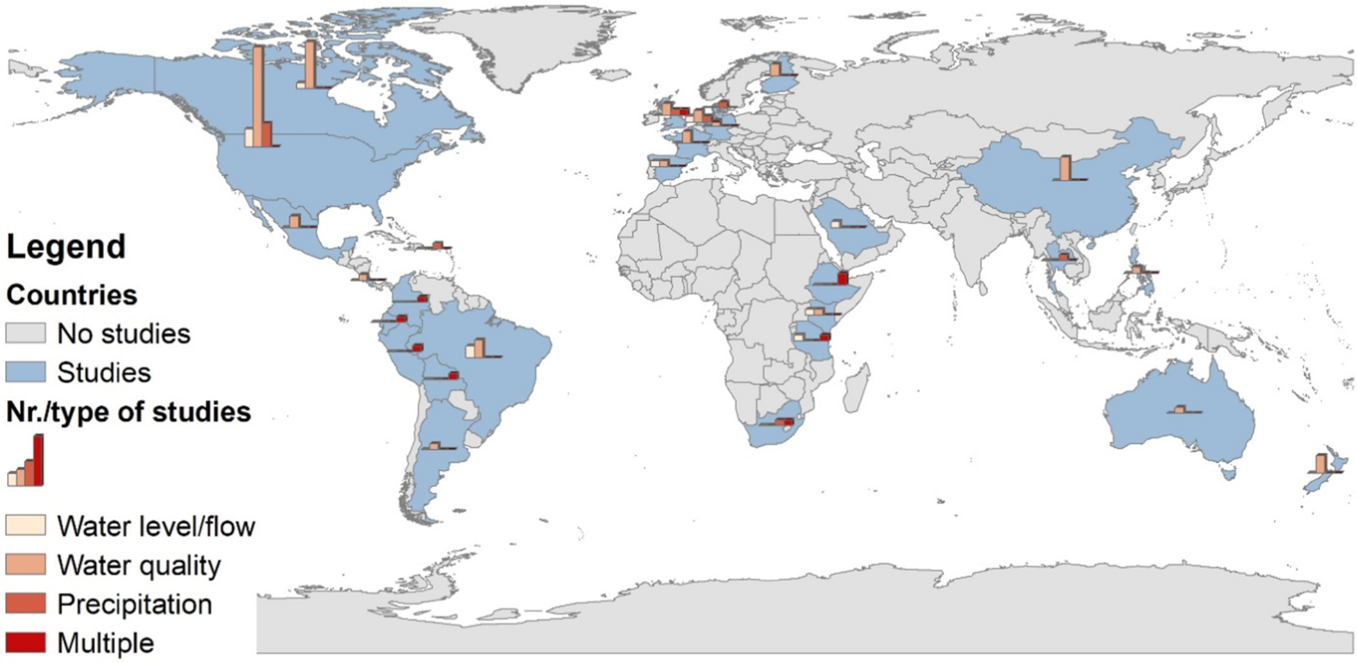

Fig. 4. Distribution of studies and scope of hydrological monitoring per country.

et al., 2017; Moffett and Neale, 2015; Weeser et al., 2018; Zemadim et al., 2013). The ways in which the participants are approached and trained differ ranging from site visits with formal training in person (Cunha et al., 2017), to instructional online videos or slide shows (Good et al., 2014) and ad hoc instruction in the field by means of signage (Lowry and Fienen, 2013; Weeser et al., 2018).

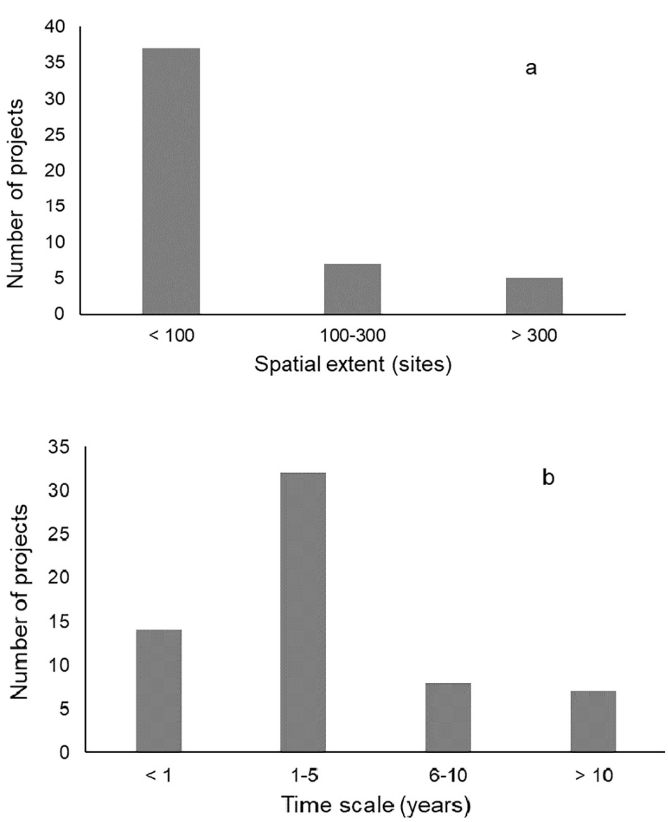

Fig. 5. (a) Spatial and (b) temporal scales of citizen science projects.

3.5. Information flows and communication channels

The majority of the citizen science programs (n = 55) had clear pathways to generate and transmit data. New technologies such as mobile applications, wireless sensor networks and online platforms show great promise for advancing citizen science. Within the reviewed studies, data collection and upload processes were either automated (i.e., data measured and uploaded via sensors or smart apps requiring some form of citizen intervention during installation), semi-automated (i.e., data collected using a sensor but uploaded manually), or manual (i.e., data manually collected, entered and uploaded by citizens). In other cases, data are submitted via paper forms and not available in real-time. In remote regions where internet connectivity is limited, data were crowdsourced using simple text messages (Weeser et al., 2018). A number of studies used a combination of several approaches to submit data such as manual recording of field data on sheets, emailing or using smartphone application (Little et al., 2016; Starkey et al., 2017). Our review reveals that use of smartphone applications is a well-established approach for data collection especially due to the ubiquity of smartphones with built-in options for positioning using global positioning systems (Dickinson et al., 2012). Some programs adopted communication strategies for retention of participants and sustainability of the projects. Continuous communication to provide feedback to participants about the data submitted, data needs, scientific purpose and importance of data being collected is considered paramount for long term participation (Lowry et al., 2019). Forms of communications such as automated feedback, newsletters, leaflets or the mass media, emails, public meetings and making the data available to the public through online databases were some of the methods applied by programs reviewed (Kongo et al., 2010; Little et al., 2016; Weeser et al., 2018; Williams et al., 2016; Wilson et al., 2018).

3.6. Water level and discharge

Streamflow monitoring is complex in nature and mostly relies on indirect measurements of flow velocity, cross-sectional area and water level to calculate the flow rate (Buytaert et al., 2014; Royem et al., 2012). In contrast, water level data are easy to collect using a citizen science approach as the measurements consist of observations comparing the level of the water with a clearly defined reference of a staff gauge (Assumpção et al., 2018; Van Meerveld et al., 2017). With the expansion of the use of mobile phones in remote regions, there are projects that have successfully engaged citizen scientists in monitoring water levels and flows using text messages. Notable examples are CrowdHydrology in the US and a citizen science-based monitoring program in Kenya (Lowry and Fienen, 2013; Weeser et al., 2018). In these projects, water level gauges alongside signboards were installed at designated stream gauging stations. Citizen scientists, who visit or pass by the sites, sent a text message with the water level reading. Both studies showed that the accuracy of the crowdsourced water level data compared with data obtained from pressure transducer data (Lowry and Fienen, 2013) and automatic radar sensor (Weeser et al., 2018) was satisfactory. In the study of Turner and Richter (2011) citizen scientists successfully mapped the occurrence of streamflow in perennial streams in dryland regions in a 12 years project. Water levels, among other variables, are part of measurements collected by citizen scientists in the FreshWater Watch (https://freshwaterwatch.thewaterhub.org) and WeSenseIt programs (Shupe, 2017; Wehn et al., 2018). Other studies have reported the successful establishment of hydrological monitoring networks for river flow and rainfall through an integrated participatory approach involving the local community (Gomani et al., 2010; Kongo et al., 2010). Kongo et al. (2010) noted that the peak flows obtained by the local community was in close agreement with results obtained from a modelling exercise from the Potshini catchment in South Africa.

With the rise in robust sensing equipment and smartphones applications embedded in cameras, web-based mapping tools and global navigation satellite systems, new approaches are emerging that are easily integrated into a citizen science context (Buytaert et al., 2014). Little et al. (2016) involved citizen scientists in the monitoring of groundwater levels in private wells using water level sounders. Citizen scientists provided valuable data on groundwater levels across a large area in Alberta, Canada and measurements were accurate when compared with data from automatic pressure transducers (root mean square error of 3–11 cm). To characterize hydrological regime for ungauged catchments, (Gallart et al., 2017), developed and tested an open source software (TREHS) based on interviews to local people. In Tanzania, local communities were involved in the collection of water level data using a smart-stick technology and taking images for discharge measurements in rivers and furrows using smartphones (iMoMo, 2018). The CrowdWater and Stream Tracker projects crowdsource hydrologic measurements including water level, streamflow and flow condition of intermittent streams. The data are collected with a smartphone application, where the user takes a picture and use the app to add virtual staff gauge and no physical installations or sensors are needed for the measurements with this approach (Kampf et al., 2018).

3.7. Precipitation

Heterogeneous distribution of observational networks limits the spatial and temporal representation of precipitation measurements, especially in less populated regions (Kidd et al., 2017). The simple design, affordability, availability and the ease of installation and operation makes manual rain gauges suited for application in citizen science (Buytaert et al., 2014). Furthermore, observing precipitation requires no advanced education in meteorology and thus crowdsourcing for precipitation has a great potential to gather data (Elmore et al., 2014). The Community Collaborative Rain, Hail and Snow network (CoCoRaHS) initiated in 1998 is probably the largest and most effective example of a citizen science-based network that involves volunteers in recording daily precipitation using low-cost tools across the US and Canada (Cifelli et al., 2005; Reges et al., 2016). The UK Community Rain Network (UCRaiN) which was inspired by CoCoRaHS, also demonstrated the potential of community-based rainfall data collection. A correlation of 0.81 was observed between the citizen and an automatic rain gauge measurement (Illingworth et al., 2014). The Phenomenon Identification Near the Ground (PING) network in the US uses a mobile application (mPING) to crowdsource high quality, spatially and temporally dense precipitation data. This data are used to improve the dual-polarization radar hydrometeor classification algorithm (Elmore et al., 2014), and to verify surface precipitation forecasts from operational numerical models (Apps et al., 2014). The Citizen Weather Observer Program is an another initiative that demonstrates how a citizen science-based approach can increase the temporal and spatial resolution of monitoring real-time meteorological data supplementing traditional networks (Bell et al., 2013).

The Internet of Things (IoT) provides new opportunities for application of citizen science to acquire vast amounts of weather data, as many people are getting connected to the internet (Meier et al., 2015). As a result of these developments, there is a growing number of automated private weather stations (PWS) that link rainfall measurements to online platforms (Bell et al., 2015; Vos et al., 2017). For instance, the user-friendly and affordable NetAtmo personal weather stations are widely distributed around the world to monitor atmospheric conditions such as temperature, humidity, air pressure, CO_2, wind and rainfall. These smart devices are automatically linked with an online platform (https://weathermap.netatmo.com/) collecting and visualizing data from all operational stations (Vos et al., 2017). Studies have shown that crowdsourced atmospheric datasets obtained from NetAtmo weather stations can contribute to urban hydro-meteorological research (Meier et al., 2015), as urban areas are characterized by a high spatial heterogeneity of rainfall, not covered by the low-spatial coverage of institutional rainfall monitoring networks. Further, the NetAtmo rainfall time series resembled measurements from a conventional high-resolution electronic gauge (Vos et al., 2017). From the aforementioned works, it is evident that high-resolution precipitation data could improve hydrological applications even in data-scarce regions. Such data can be obtained through citizen science monitoring, especially with the advent in technology and new innovative data collection techniques.

3.8. Water quality

Citizen science has been widely used to monitor water quality in lakes, streams, rivers, wells, ponds, and wetlands (Conrad and Hilchey, 2011). Currently, various organizations in several countries around the world are involved in collaborative efforts and support volunteer-based water quality monitoring programs (Deutsch and Ruiz-Córdova, 2015). Water quality data are essential to improve the management effectiveness of surface water systems (Zheng et al., 2018). The World Water Monitoring Day initiative (http://www.worldwatermonitoringday.org/) established by the America's Clean Water Foundation (ACWF) is a worldwide educational outreach program that uses online means to recruit and engage citizens in protecting water resources and empowering them to conduct basic water quality monitoring of their local water bodies (EarthEcho, 2015). A similar scheme is coordinated by Community Science Institute in New York, to produce data that inform water resource management while simultaneously educating and empowering citizens to become stewards of their local environment (Community Science Institute, 2017). The Florida Lakewatch, and Alabama Water Watch (AWW) are successful examples of long-term volunteer water quality monitoring programs, working with thousands of citizen scientists for over ten years to study fresh-water ecosystem dynamics and generating information on >1500 water bodies (Deutsch and Ruiz-Córdova, 2015; Hoyer et al., 2014; Thornhill et al., 2018).

Although most citizen-science water quality programs collect data in the form of water samples (Breuer et al., 2015; Good et al., 2014), others involve in situ monitoring of parameters like turbidity and nutrient concentrations or ecosystem health indicators such as macroinvertebrates or *Escherichia coli* (Latimore and Steen, 2014; Scott and Frost, 2017; Thornhill et al., 2017). Various methods and techniques have been reported for different programs. They span from simple test kits to measure water quality parameters such as dissolved nitrate and orthophosphate, such as in the FreshWater Watch program (Shupe, 2017) or the World Water Monitoring Day initiative (EarthEcho, 2015). In other cases, citizens are involved in the visual assessment of water color, smell and surrounding conditions ((Zheng et al., 2017). In the Sondu catchment of Kenya, a citizen science-based project engages citizen scientists in monitoring water levels and quality (Table 2). Nitrate levels are measured using simple colorimetric methods (Gräf, 2018). Secchi disks and turbidity tubes have been widely used in volunteer monitoring for water turbidity (Toivanen et al., 2013), and have been successfully applied in the Sondu catchment. Gräf (2018) tested the 'tampon method' using inexpensive passive samplers to detect optical brighteners in the surface waters of the Sondu catchment. Here, the community wash their clothes in the streams and it was hypothesized that optical brighteners from detergents could be detected downstream. In urban areas, optical brighteners are strong indicators of misconnected drainage in surface waters (Chandler and Lerner, 2015). However, application of this approach in streams could be influenced by high concentration of suspended sediments as demonstrated in the Sondu catchment (Gräf, 2018), and the method could be improved especially by protecting the tampons and sampler from sediments to improve accuracy.

Photos courtesy of Patrick Shepherd, Centre for International Forestry Research (CIFOR).

The increasing appeal in participatory research, advent of internet connectivity and low-cost sensing equipment improved monitoring capabilities for water quality. Projects are now increasingly adopting modern data collection and transmission technologies and making use of integrated sensing systems with multi-parameter monitoring (Kotovirta et al., 2014). Applications such as the automatic Secchi3000 (Toivanen et al., 2013), KdUINO ((Bardaji et al., 2016) and Hydrocolor (Leeuw et al., 2018) have been used and validated to measure water turbidity with citizens. Overall, the recently developed monitoring systems are cost-effective, portable, offer continuous real-time water quality monitoring and cloud data storage possibilities, and are easy to use with minimal training.

3.9. Social media

Researchers are increasingly mining volunteered geographic information such as images and videos shared via social media (e.g., Facebook, YouTube, Twitter and Flickr) to estimate water levels, flow velocities and discharges (Boursicaud et al., 2016; Fohringer et al., 2015; Le Coz et al., 2016; Michelsen et al., 2016). This sort of heterogeneous and complex information has, for instance been applied in hydrology for real-time mapping, to understand the dynamics of flood processes and to validate models for the prediction of flood events (Li et al., 2018; McDougall, 2011; Smith et al., 2017). Some of the studies reported (Table 3) did not actively involve or engage with the public directly like other deliberate citizen science approaches, hence the participants are probably unaware of their contribution and participation in a scientific study (Daume et al., 2014; Michelsen et al., 2016).

3.10. Data credibility and application of citizen science data

Given the heterogeneity of citizen science based monitoring, most programs develop and adopt rigorous quality assurance/quality control measures for quality assessment to ensure the production of scientifically valid water data. The United States Environmental Protection Agency provides support to volunteer water quality monitoring programs by developing guidelines, manuals and toolboxes that are essential for communities (English et al., 2018). During the initiation phase of most projects, citizen scientists are provided with monitoring protocols, materials, equipment and training on water monitoring. Several recent studies have assessed the quality of the citizen science water quality data to account for data standards and reliability. Studies that compared volunteer versus professional datasets or with standard methods suggest that citizen scientists generate high-quality data which is comparable to professional data (Aceves-Bueno et al., 2017; Canfield Jr et al., 2002; Hoyer et al., 2014; Loperfido et al., 2010; Nicholson et al., 2002; Storey et al., 2016). Fore et al. (2001) compared volunteer and professional monitoring of benthic macroinvertebrates as bio-indicators of water quality, reporting similar data quality. Water temperature and dissolved oxygen data in stream and rivers collected by scientists from the US Geological Survey and citizen scientists showed that both measurements are in the same range, although volunteer measurements underestimated dissolved oxygen levels (Safford and Peters, 2018). Aceves-Bueno et al. (2015) reviewed 83 citizen science studies and reported only one case of insufficient data quality associated with citizen science generated data.

Some organizations use and combine citizen scientists data as part of their research activity, which is an indication that scientists considered these datasets to be of sufficient quality for research (Follett and Strezov, 2015). In the US, the IOWATER volunteer water quality monitoring program supplements the information used by the government for regulatory purposes (Loperfido et al., 2010). Thornhill et al. (2018) used the FreshWater Watch datasets to explore the effect of increasing urbanization on the seasonal, chemical, and biological conditions of ponds and lakes. Elsewhere, Wang et al. (2018) used the data accrued by the Community Science Institute (CSI) to model stream *Escherichia* spp. concentrations and loadings. Koskelo et al. (2012) used rainfall data from the Weather Underground (WU) website (https://www.wunderground.com/) to quantify the spatial variability in rainfall and baseflow and not base-flow separation for small watersheds. Lincoln

Table 2
Citizen science-based water monitoring in Sondu Catchment, Kenya.

Parameter	Water levels	Optical brighteners	Nitrate	Turbidity
Method	Manual water level gauges at fixed locations. and a signage to provide instructions	A tampon fixed at a small metal bar. Presence of optical brighteners checked with a UV-torch light.	Dissolved nitrate measured from unfiltered samples using nitrate strips. Nitrate concentration estimated by comparing the resultant reaction to a reference chart with specific ranges.	Water turbidity determined through a calibrated turbidity tube, which is filled with water until the marking at the bottom is no longer visible when viewed from above. Turbidity is estimated against a turbidity unit scale.
Example				

Table 3
Contribution of citizen science in hydrology through social media.

Reference	Location	Type of data	Application
Boursicaud et al. (2016)	France	Video of a flash flood event shared via social media (YouTube)	Estimation of water level, surface flow velocities and discharges
Le Coz et al. (2016)	Argentina, France and New Zealand	Video sent through the website	Estimation of water level/surface flow velocities and discharges
Michelsen et al. (2016)	Saudi Arabia	Videos and photographs shared on social media via YouTube	Analysis of water level time series
Li et al. (2018)	USA	Texts and pictures shared via Twitter	Flood mapping
McDougall (2011)	Australia	Photographs and videos shared via Twitter and Facebook	Mapping of flood extent
Fohringer et al. (2015)	Germany	Photographs shared via Twitter and Flickr	Analysis of water level and flood inundation mapping.
Smith et al. (2017)	UK	Pictures and texts posted via Twitter	Modelling

et al. (2017) utilized >200 rainfall reports obtained by citizen scientists in different programs to improve the analysis of severity and scope of the North Central Gulf Coast historic rainfall event that occurred on April 2014. Organizations such as the US National Oceanic and Atmospheric Administration and the National Hydrologic Warning Council have integrated ground observations of precipitation obtained from CoCoRaHS monitoring network into their work to validate radar precipitation estimations and that obtained from automated rain gauge networks (Kluver et al., 2015; Simpson et al., 2017; Smith et al., 2015; Zhang et al., 2014). There are practical applications in the Netherlands, where 20 amateur stations were used to quantify the heat-island effect in urban areas (Wolters and Brandsma, 2012).

3.11. Data transmission

The growth in open science including the development of customizable mobile applications, scientific instrumentation and data storage technologies has increased the efficiency for direct and rapid data upload, validation and visualization of data on web-based databases (Little et al., 2016). Notably, these developments play a great role towards overcoming the potential for errors that come with manually recording and uploading data or loss of vast amounts of information produced (Curtis, 2018). Crowdwater (Kampf et al., 2018), Creekwatch (Kim et al., 2011), and Crowdmap (Ross and Potts, 2011) present mobile apps used to harness the power of citizen scientists to collect hydrologic data. Nowadays, citizen scientists can also collect data through images and videos with geo-located date and time-stamped information that can be used for further analyses. For instance in Creek Watch, a smartphone application allows to submit photos and qualitative stream data about water level, water flow rate and amount of litter along waterways (Kim et al., 2011). The applications are non-intrusive, cost-effective, portable and measurements are transmitted to a cloud database and automatically synchronized to be managed, analyzed and shared or exported. Additionally, the setup of the websites allows data validation, visualization, and real-time mapping of results (Bell et al., 2013) such as the Weather Underground (https://www.wunderground.com/), UK Met Office Weather Observation Website (http://wow.metoffice.gov.uk/). These websites provide an open platform for citizens to share weather data online with the wider community (Vos et al., 2017). Similarly, cloud-based storage has now become the standard means to store data, which facilitated the rapid growth in citizen science. Cloud server and storage solutions are low-cost, scalable allowing for platforms to be easily developed via application programming interfaces (APIs) to display large datasets in real-time to end-users (Chapman and Bell, 2018).

3.12. Future developments

Camera-based systems are increasingly used to collect environmental data because images and videos are more informative and intuitive than other crowdsourcing methods (Jiang et al., 2019). Large-Scale Particle Image Velocimetry (Tauro et al., 2017) and DischargeApp (iMoMo, 2018) methodologies have increased the ability to conduct streamflow measurements. However, camera-based approaches are still limited in hydrology. Royem et al. (2012) developed a low-cost monitoring system based on a digital camera to measure water level, which showed good agreement with water levels measured traditional gauging stations. This method is simple enough to be applied in citizen science. Allamano et al. (2015) introduced a novel technique based on the quantitative detection and measuring of rainfall intensity from pictures of rainy scenes. Other studies demonstrated the use of *in situ* digital cameras, wireless sensor networks and other smartphone-based systems for real-time water quality monitoring (Goddijn-Murphy et al., 2009; Rasin and Abdullah, 2009; Srivastava et al., 2018). Sakai et al. (2018) developed and validated ECO-Heart, a simple tool for a community-based water quality assessment, which was used to monitor six parameters: pH, heavy metals, chemical oxygen demand, transparency, ammonia nitrogen and dissolved oxygen. Similarly, in remote regions such as mountain streams where physical installation of staff level gauges or sensors or camera-based systems to monitor water level is difficult, a virtual staff gauge approach could be used (Seibert et al., 2019).

4. Conclusions

This review shows that it is possible to successfully engage the public in hydrological monitoring. Hydrological citizen science monitoring programs can generate extensive datasets with broad spatial and temporal coverage. Most programs recruit and train participants and through validation and calibration, researchers have found that citizen scientists collect data comparable to professional data. Effective communication strategies have to be implemented to promote sustainability such as games for education, making data publically available (e.g. via websites, public meetings with scientists, newsletters and/or social media), developing interactive webpages, and providing automated feedback. In most projects, the role of citizen scientists is limited to information and data collection. Future citizen science in hydrology could benefit from more co-created types of projects to establish stronger ties between research and communities that lead to public engagement, thereby enhancing sustainability of monitoring networks.

An emerging area of research is the mining of volunteered geographic information from social media. Information shared through social media could provide highly valuable hydrological data that can offer direct insights in flow rate and help improve the understanding of extreme hydrological events. Moreover, the analysis of hydrological data from social media may support a better understanding of the interactions between humans and the environment for shaping future environmental management. Hence, future studies can benefit from crowdsourcing information of hydrological relevance from social media to improve the spatial coverage of the hydrological measurements. All these findings demonstrate the potential of citizen science networks to collect reliable, timely and long-term hydrological data, which is very important information for planning and management purposes. Possible developments are expected to draw large benefit from rapid technological advancements in sensors and from the massive penetration of smartphone technologies, especially in low-income countries as well.

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Appendix A. Appendix (referred in Section 3.1)

Table 4
Overview of citizen science application in hydrological monitoring.

Reference	Location	Number of sites/ participants/ measurements	Time scale	Monitoring Focus	Training	QA/QC	Data transmission	Type of project	Program
Abbott et al. (2018)	France	13 sites	18 years	Water quality	n.s.	n.s.	n.s.	Contributory	Ecoflux
Bardaji et al. (2016)	Spain	2 sites	n.s.	Water quality	yes	yes	n.s.	Collaborative	
Breuer et al. (2015)	Germany	280 sites	1 day	Water quality	yes	yes	Grab water samples delivered to lab	Contributory	HydroCrowd
Brouwer et al. (2018)	Netherlands	85 sites/ 85 participants	n.s.	Water quality	yes	yes	Online survey -SurveyMonkey software	Contributory	Freshness of Water
Canfield Jr et al. (2002)	US	125 sites	>10 years	Water quality	yes	yes	Manual recording - data sheets	Contributory	Florida LAKEWATCH
Cifelli et al. (2005)	US	>1000 participants	7 years	Precipitation	yes	yes	CoCoRaHS webiste	Collaborative	CoCoRaHS
Cunha et al. (2017)	Brazil	64 sites	4 months	Water quality	yes	yes	Grab water samples	Contributory	Freshwater watch
Reutebuch et al. (2008)	US	>1950 sites/ >4,700 participants	>15 years	Water quality	yes	yes	Alabama Water Watch server	Collaborative	Alabama Water Watch
Deutsch et al. (2005)	Phillipines	n.s.	>5 years	Water quality	yes	yes	n.s.	Collaborative	
Edwards et al. (2018)	US	n.s.	7 years	Water quality	yes	yes	n.s.	Collaborative	
Edwards, (2016)	US	3 sites	11 years	Water quality	yes	yes	n.s.	Contributory	
Elmore et al. (2014)	US	n.s.	4 months	Precipitation	yes	yes	Mobile application (MPING)	Contributory	
Farnham et al. (2017)	US	23 sites	>2 years	Water quality	n.s.	yes	Grab water samples delivered to lab	Contributory	
Flores-Díaz et al. (2018)	Mexico	30 sites	>5 years	Water quality	yes	yes	n.s.	Collaborative	Global Water Watch
Gomani et al. (2010)	Tanzania	39 sites	n.s.	Water level & flow, precipitation, and ground water level	n.s.	n.s.	n.s.	Collaborative	Resilient Agro-landscapes to Climate Change
Good et al. (2014)	US	>125 participants/ 685 measurements	1 day	Precipitation	yes	yes	Grab water samples delivered to the laboratory for analysis	Contributory	
Illingworth et al. (2014)	UK	13 sites	>1 month	Precipitation	yes	yes	Email or Twitter	Contributory	UCRaiN- the UK Citizen Rainfall Network
Jollymore et al. (2017)	Canada	n.s.	1 year	Water quality	n.s.	yes	Grab water samples delivered to the laboratory for analysis.	Contributory	Waterlogged citizen science campaign
Koch & Stisen (2017)	Denmark	n.s.	2 months	Precipitation	n.s.	n.s.	n.s.	Contributory	
Kongo et al. (2010)	South Africa	n.s.	2 years	Streamflows & precipitation.	yes	yes	Manual recording- data sheet	Collaborative	
Kosgei et al. (2007)	South Africa	3 sites	1 year	Precipitation	yes	yes	n.s.	Collaborative	
Kotovirta et al. (2014)	Finland	320 sites/ 872participants	3 years	Water quality	yes	yes	Hydrocolor mobile application	Contributory	
Leeuw et al. (2018)	USA	14 measurements	1 day	Water quality	yes	yes	Smartphone application	Contributory	
Lévesque et al. (2017)	Canada	28 sites/ 69 participants	>2 years	Water quality	yes	yes	Smartphone application	Contributory	Freshwater watch
Little et al. (2016)	Canada	40 sites	5 years	Water level	yes	yes	Telephone, fax or email and web portal	Contributory	

Table 4 (*continued*)

Reference	Location	Number of sites/ participants/ measurements	Time scale	Monitoring Focus	Training	QA/QC	Data transmission	Type of project	Program
Loiselle et al. (2016)	Argentina, Brazil, Mexico and Canada	150 sites/ 1000 participants	2 years	Water quality	yes	yes	Online upload	Contributory	Freshwater watch
Lowry and Fienen (2013)	USA	9 sites/ 150 measurements	>6 months	Water level	none	yes	Simple text message	Contributory	Crowdhydrology
McGoff et al. (2017)	United Kingdom	76 sites	3 years	Water quality	yes	yes	Smartphone applicatin	Contributory	Fresh water watch
Michelsen et al. (2016)	Saudi Arabia	16 videos	1 year	Water level	none	yes	Sharing of videos and photographs on YouTube.	Contributory	
Moffett and Neale (2015)	New Zealand	21 sites	11 years	Water quality	yes	yes	n.s.	Contributory	
Ochoa-Tocachi et al. (2018)	Peru, Ecuador and Bolivia	9 sites	n.s.	Precipitation and stream flow	n.s.	yes	n.s.	Contributory	Initiative for Hydrological Monitoring of Andean Ecosystems
Reges et al. (2016)	USA, Puerto Rico, US Virgin Islands, and Canada	>50 states/ >20,000 participants	>10 years	Precipitation	yes	yes	CoCoRaHS website	Collaborative	
Shahady & Boniface (2018)	Costa Rica	16 sites	2 years	Water quality	yes	yes	Manual recording -data sheet	Contributory	
Shupe (2017)	Canada	81 sites	4 years	Water quality	yes	yes	Manual recording and smartphone app in online database	Contributory	Freshwater watch
Starkey et al. (2017)	Britain	10 sites	>2 years	Water level, precipitation and water quality	yes	yes	Web forms, spreadsheets, email, meetings, and Android app	Contributory	
Storey & Wright-Stow (2017)	New Zealand	8 sites	>1 year	Water quality	yes	yes	n.s.	Contributory	
Storey et al. (2016)	New Zealand	11 sites/ 77 participants	>1 year	Water quality	yes	yes	n.s.	Contributory	
Thornhill et al. (2018)	UK, France, Netherlands, US, Canada & Australia	75 sites/120 participants	2 years	Water quality	yes	yes	n.s.	Contributory	Fresh water watch
Toivanen et al. (2013)	Finland	100 participants/1146 measurements	1 year	Water quality	n.s.	yes	Smartphone application	Contributory	
Walker et al. (2016)	Ethiopia	8 sites	>1 year	Precipitation, stream water level & groundwater levels	yes	yes	Manual recording-data sheet	Collaborative	AMGRAF
Weeser et al. (2018)	Kenya	13 sites/ 125 participants/ 1175 measurements	1 year	Water level	yes	yes	Simple text message	Contributory	
Wendt et al. (2018)	USA	131 sites/ >50 participants	n.s.	Water quality	yes	yes	n.s.	Contributory	
Williams et al. (2016)	USA	424 sites/ 248 participants	10 years	Water quality	yes	yes	Direct online upload and grab samples delivered to lab	Contributory	Trout Unlimited
Wilson et al. (2018)	Canada	54 sites	8 years	Water quality	yes	yes	n.s.	Contributory	
Wiwatwattana et al. (2015)	Thailand	25 participants/ 301 measurements	140 days	Precipitation	yes	yes	Facebook applicatin (SWUA)	Contributory	
Xu et al. (2017)	China	8 sites	>2 years	Water quality	yes	yes	Direct upload to online database	Contributory	Freshwater watch
Zemadim et al. (2013)	Ethiopia	28 sites	n.s.	Precipitation, water level, groundwater level	yes	yes	Submitted monthly hard copies	Collaborative	
Zhang et al. (2017)	China	31 sites	4 years	Water quality	yes	yes	Smartphone app or by internet to online database	Contributory	
Zheng et al. (2017)	China	30 provinces/ 219 measurements	>1 year	Water quality	yes	yes	Smartphone application	Contributory	Freshwater watch

(continued on next page)

Table 4 (*continued*)

Reference	Location	Number of sites/ participants/ measurements	Time scale	Monitoring Focus	Training	QA/QC	Data transmission	Type of project	Program
Engel & Voshell (2002)	USA	145 sites	2 years	Water quality	yes	yes	Manual recording-data sheets	Contributory	Virginia-Save-Our-Streams program
Nerbonne & Vondracek (2003)	USA	n.s.	2 years	Water quality	yes	yes	Manual recording-data sheets	Contributory	
Barrows et al. (2018)	USA	72 sites/ 117 participants	2 years	Water quality	yes	yes	Smartphone app, manual recording-datasheets & grab water samples delivered to lab	Collaborative	
Compas & Wade (2018)	USA	2 participants/ >30,000 measurements	11 days	Water quality	yes	yes	Smartphone application	Contributory	Testing the Waters
Dorset Environmental Science Centre (2015)	Canada	>800 sites/ >600 participants	3 years	Water quality	yes	yes	n.s.	Contributory	Lake Partner Program
Fava et al. (2014)	Brazil	n.s.	n.s.	Water level	n.s.	n.s.	Mobile application	Contributory	
Alfonso et al. (2010)	Netherlands	4 sites/ 4 participants	1 month	Water level	n.s.	yes	Simple text message	Contributory	
Degrossi et al. (2014)	Brazil	10 participants/ 15 measurements	n.s.	Water level	yes	yes	Smartphone application	Contributory	
Turner and Richter (2011)	USA,	n.s.	12 years	Water level	yes	yes	Manual recording-data sheet	Contributory	
Kim et al. (2011)	USA	65 measurements	3 weeks	Water level, flow rate and trash	yes	n.s.	Mobile app	Contributory	
Muenich et al. (2016)	USA	206 sites/ 889 participants	5 years	Water quality	yes	yes	n.s.	Collaborative	
Vos et al. (2017)	Netherlands	63 sites	4 months	Precipitation	n.s.	yes	Direct upload through Wi-Fi connection	Collaborative	
Gallart et al. (2017)	Spain	119 sites	n.s.	Water flow	n.s.	n.s.	Questionnaire	Contributory	
García and Brown (2009)	Colombia	38 sites/ 30 participants	2 years	Water quality and water flows	yes	yes	n.s.	Co-created	
iMoMo (2018)	Tanzania	24 sites	6 years	Water flows	yes	yes	Simple text message and smartphone application	Co-created	iMoMo Global Initiative.
EarthEcho (2015)	Global	146 countries	>11 years	Water quality	yes	yes	Direct upload online to a central database.	Co-created	World Water Monitoring Challenge
Macknick & Enders (2012)	USA	19 sites/ 70 participants	> 1 year	Water quality	yes	n.s.	Grab samples	Contributory	
Castilla et al. (2015)	Brazil & China	13 cities	> 1 year	Water quality	yes	yes	Smartphone app	Contributory	Fresh Water Watch
Latimore and Steen (2014)	USA	> 500 sites	n.s.	Water quality	yes	yes	n.s.	Contributory	MiCorps
Scott and Frost (2017)	Canada	29 sites/111 participants	3 years	Water quality	yes	yes	Smartphone application	Contributory	Fresh Water Watch
Gräf (2018)	Kenya	6 sites	< 1 year	water quality	yes	yes	Simple text message	Contributory	
Stepenuck et al. (2011)	USA	6 states/ 150 participants	2 years	Water quality	yes	yes	Grab samples delivered to lab	collaborative	

*n.s. = not specified.

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