How citizen scientists can enrich freshwater science as contributors, collaborators, and co-creators

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Abstract: The involvement of volunteers in aspects of freshwater research and monitoring has a long history. However, the advent of smart technology and access to the internet has opened up the possibility of mass public participation in science, termed citizen science. The potential of citizen science to generate data over wider spatial and temporal scales than conventional approaches is well recognized. However, as the field of citizen science has matured, more attention is being given to the participant journey, and how practitioners can maximize engagement. The papers in this special series on citizen science and freshwater are collected from a range of initiatives, with each study operating in different environments and engaging with citizens with contrasting socioeconomic circumstances. Many of the studies result in insights into freshwater biodiversity (e.g., amphibians, fish, wetland birds), whereas others explore the abiotic environment (e.g., water quality, flow regimes). In addition, several papers assess volunteer participation dynamics and provide guidance for those considering the use of citizen science. The use of citizen science in freshwater science is growing and so too is the quality of the scientific outputs. In part, this growth has been caused by a gradual evolution and expansion in the approach, which involves volunteers as contributors, collaborators, and co-creators. This flexibility holds great promise for opening a new source of valuable freshwater data and knowledge.
Key words: citizen science, volunteer monitoring, participation, community-based monitoring

The involvement of volunteers in freshwater science has a long history. For example, volunteer stream monitoring has been occurring for decades throughout the United States (e.g., USEPA 1997) and the UK (Brooks et al. 2019, *this issue*). However, the widespread ownership of smart technologies and mobile access to the Internet has resulted in a recent surge of interest in public participation in science, termed 'citizen science' (Bonney et al. 2014). The significant *potential* of citizen science to contribute to scientific research (Silvertown 2009), environmental monitoring (Pocock et al. 2018a), education (Bonney et al. 2009), and public engagement with science (Dickinson et al. 2012) is now firmly recognized, but the science underpinning citizen science is a more recent concern, and as a result, this potential is not always realized (Jollymore et al. 2017).

Volunteers are often able to provide data comparable to those collected by professional scientists (Crall et al. 2011, McGoff et al. 2017), but their ability to do so depends upon the resolution at which the comparisons are made (Lukyanenko et al. 2016). Quality control is a frequent concern regarding citizen science derived data (Storey et al. 2016, Jollymore et al. 2017). In addition, reliance on volunteers can lead to both spatial (Flanagin and Metzger 2008) and temporal biases in data collection (Thornhill et al. 2016). To address these issues, many frameworks and protocols have been developed that are designed to improve the accuracy and precision of data acquisition and management (e.g., Pocock et al. 2014, Shirk and Bonney 2015). Moreover, it has been recognized that, if carefully designed, citizen science initiatives have particular value complementing rather than substituting for conventional regulatory monitoring (Hadj-Hammou et al. 2017). Citizen science, in particular, holds the potential to directly facilitate more sustainable use of freshwater resources through awareness raising and behavior change among volunteers.

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The development of citizen science infrastructure (e.g., guides, protocols, citizen science organizations) indicates an increasing sophistication in the scientific use of volunteered information. As the field has matured, so too has the quality of related scientific outputs and publications (Fig. 1), and the practice of citizen science is increasingly recognized within Europe and North America (e.g., Citizen Science Associations), and supported by respective funders.

In contrast to regulatory monitoring and assessment, citizen science initiatives are dependent upon the motivations of unpaid volunteers, which have not always received due consideration in project design. An understanding of participant motivations must be gained at the onset of a project and should inform methods and expectations of the researchers and participants. For example, such considerations are embedded into the European Citizen Science Association's 'Ten principles for citizen' (Robinson et al. 2018). However, quantifiable evidence regarding what motivates people to participate in science is still underdeveloped. Further, motivations are likely to vary according to people's inherent regard for nature, occupation, age, and wealth (Geoghegan et al. 2016). Other factors that influence the longevity of involvement by a project participant may relate to a feeling of community (participant to participant and participant to scientist engagement), the quality of training given (August et al. 2019, *this issue*), the condition of the environment they are to survey (Marsh et al. 2019, *this issue*), or the role of participant in the design process (Irwin 2018). This latter point also reflects participant confidence, a lack of which has been found to deter continued involvement (Storey et al. 2016). Nevertheless, following Pareto's principle (Pareto and Page 1971), the majority of data are collected by a relative few highly motivated and dedicated volunteers, complemented by a turnover of short-term participants (West and Pateman 2016).

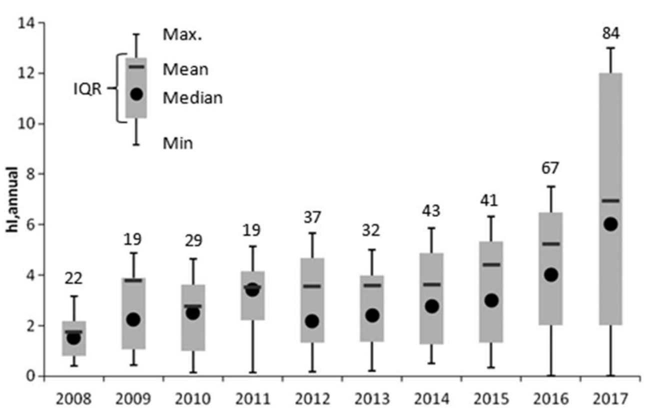

Figure 1. Annualized *h*-index (Hirsch 2005) as an indicator of the growing value of freshwater citizen science over the last decade (2008–2017). Annualized *h*-values were derived from 6000 Google Scholar records of citizen science papers in freshwater science produced from a search of 6 terms (see Appendix S1 for the full method and search terms). The number of citizen science papers published in a given year is given above each boxplot. IQR = Inter-quartile range, the difference between the 75^{th} and 25^{th} percentiles.

These inherent differences in volunteer motivations mean that different approaches work for different groups of people. Concomitantly, citizen science has evolved substantially from traditional expert volunteer data gathering to everything from passive data collection with smart phones to volunteer-led community action. In response to this evolution, progress toward maximizing engagement has been especially notable among 3 key types of citizen science within freshwater research: contributory, collaborative, and co-created science. Several typologies exist (e.g., Buckingham Shum et al. 2012, Haklay 2013), but Miller-Rushing et al. (2012) identify these 3 categories of project according to the depth of participation, each of which is evident across the contributions to this special series.

CONTRIBUTORY

In contributory projects, participants provide resources otherwise unattainable by a small team of scientists. Contributions may include providing regular counts of wetland birds (Yardi et al. 2019, *this issue*) or the endangered European eel (*Anguilla anguilla*) (Pecorelli et al. 2019, *this issue*), the collection of biotic or abiotic samples in mountainous catchments (Křeček et al. 2018, *this issue*), or the recording of wetted reaches of intermittent desert streams (Allen et al. 2019, *this issue*). Comparable to crowdsourcing (Buckingham Shum et al. 2012), participation in a contributory project requires minimal cognition on the part of the volunteer, but such projects can produce data that cover wide spatial and temporal scales. A contemporary example of contributory projects are 'blitz' events, which aim to collect as much data as possible about a particular area in a constrained period of time (Muenich et al. 2016).

COLLABORATIVE

In collaborative projects, participants provide not only data, but may also help to refine the project design, analyze data, or disseminate findings (Miller-Rushing et al. 2012). In this sense, intelligence is distributed, and the citizen operates as a basic data interpreter. For example, FreshWater Watch (FWW) is an international citizen science program that underpins 5 of the studies in this special series. In FWW, participants receive one day of training, are provided with a kit that enables them to test water quality in situ, receive feedback through multiple channels, and are encouraged to disseminate findings. The use of this standardized approach to a global program has permitted comparisons of the effect landscape structure has on stream-water quality in the Americas (Cunha et al. 2019, *this issue*) and tests of the assumed impacts of urbanization across 6 major conurbations (Miguel-Chinchilla et al. 2019, *this* *issue*). Alternatively, such an approach can be tailored to local situations in collaboration with local communities or their representatives, e.g., to test for potential human and environmental health implications of agricultural practices within an iconic wetland (Pérez Belmont et al. 2019, *this issue*) and the effectiveness of wetland eco-restoration (Yardi et al. 2019, *this issue*). Similarly, the Angler's Riverfly Monitoring Initiative (ARMI) trains volunteers to collect, as well as analyze, invertebrate samples before their data are uploaded to a publicly accessible database (Brooks et al. 2019, *this issue*). Once uploaded to a publicly accessible database, ARMI data are compared with regulatory agency guidelines, repeated breaches of which can trigger formal pollution investigation.

CO-CREATED

Co-created projects are those designed by scientists and members of the public working together in every stage of project development. Such projects are uncommon relative to contributory or collaborative projects, and their objectives may differ from scientific research. For example, Weigelhofer et al. (2018, *this issue*), describes the joint development of biogeochemical experiments within a high-school curriculum. Furthermore, in co-created projects, professional scientists may facilitate projects where non-professionals are the key drivers. To this end, the paper by Dawson et al. (2018, *this issue*) was possible only as a result of access to scientific equipment used within a collaborative citizen science initiative.

LOOKING AHEAD

The field of citizen science continues to evolve with new methods to encourage mass participation and improvements to the citizen science infrastructure. For example, different approaches are required where internet access and digital literacy are low. Similarly, innovation is needed to develop culturally-relevant citizen science in low- and middle-income countries (Pocock et al. 2018b), and to develop methods and metrics to evaluate how well a citizen science approach advances scientific discovery, democracy, social innovation, and economic development. The potential that citizen science offers for both high-quality data collection and deep engagement of citizens is increasingly recognized by governments (European Commission 2014), environmental protection agencies (Owen and Parker 2018), and inter-governmental organizations (Bowen et al. 2017). This potential makes it highly likely that funding opportunities will increase, and projects and programs will continue to expand in both scale and impact, potentially transforming the future of freshwater research and conservation.

This special series is a significant and timely contribution to this growing field and provides insight into both the capacity of citizen science to operate in developing and developed nations as well as across different freshwater ecosystem components. The studies in this special issue demonstrate the breadth of freshwater research questions that can be addressed through citizen science and the great variety of approaches that have been developed to date. Such variety in approach has been greatly facilitated by using common platforms and methods like FWW, which increase project cost-effectiveness, study scalability, and data quality (Thornhill et al. 2018). Crucially, the FWW platform and method also provide sufficient flexibility to adapt to the specific needs of individual studies (e.g., by facilitating addition of environmental variables) and their volunteers. This flexibility holds great promise for opening a new source of valuable freshwater data and knowledge. Furthermore, modern citizen science programs should increase the number of engaged and informed citizens who take action for a more sustainable environment in their personal and professional lives (Ceccaroni and Piera 2017).

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