Groundwater

Methods Note/

Are Groundwater Level Data Collected by Citizen Scientists Trustworthy? A Cautionary Tale

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Abstract

Public participation in groundwater projects is increasing, however, the efficacy of the data collected in such studies, is not well-documented in the literature. In this study, the authors describe a citizen science project focused on measuring and recording groundwater levels in an aquifer and evaluate whether the groundwater data collected by the participants are trustworthy. A total of 31 participants were initially recruited to measure and record groundwater levels from 29 monitoring wells on a barrier island. Following recruitment, the authors provided training to the citizen scientists by introducing groundwater concepts, and showing the participants how to measure, record and report groundwater level data (over an 81-day period) with an electronic water level meter. The water level data recorded by the citizen scientists (i.e., 35 time series datasets with over 450 unique measurements) were then compared to high frequency data recorded by automated water level loggers that were already deployed in the groundwater monitoring wells to assess the trustworthiness of the data. Trustworthiness was evaluated using measures of reliability (i.e., consistency in measuring the same thing), validity (i.e., degree to which results are truthful), and other standard graphical and statistical techniques. The results suggest that with proper training, guidance, and motivation, citizen scientists can collect trustworthy groundwater level data that could be useful for monitoring the sustainability of aquifers and managing of groundwater levels. It is noted however, that such positive outcomes require significant investments of time and effort on the part of the project managers.

Introduction

Groundwater level data are important for describing groundwater flow regimes as well as understanding interactions between groundwater and surface water systems (e.g., Giese et al. 1991; Barlow 2003; Sherif et al. 2012; Manda et al. 2015). Owing to the costs involved with installing and managing groundwater monitoring wells and automated water level loggers, sustaining extensive groundwater monitoring programs for long periods of time may be too demanding on available resources. An alternate option is to use citizen science to address this shortcoming.

Citizen science, which is the public participation of nonscientists in scientific research (Dickinson and Bonney 2012; Johnson et al. 2014), is a tool that is useful for connecting the public to the scientific community with the goal of expanding scientific knowledge and literacy (Bonney et al. 2009). As a result, citizen scientists are increasingly being sought to collect environmental data across various temporal and spatial scales to meet various

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needs in many parts of the world (e.g., Hidalgo-Ruz and Thiel 2013; De Coster et al. 2015; Dennhardt et al. 2015; Jackson et al. 2015; Newson et al. 2015; Grace-McCaskey et al. 2019). Citizen science therefore provides a mechanism for engaging active, participatory stakeholders in science with the added benefit of raising awareness of hydrologic processes (e.g., flooding related to sea-level rise) (Grace-McCaskey et al. 2019; Etheridge et al. 2020) while extending across social networks (Yusuf et al. 2018).

The use of citizen scientists in hydrologic studies is not necessarily novel; citizen scientists have been used in various types of hydrologic studies, and at different levels of engagement (Buytaert et al. 2014; Etheridge et al. 2020). For example, the long-running (>20 years) CoCoRaHs project (Cifelli et al. 2005) has used citizen scientists to collect precipitation data across the entire United States. In this project, citizen scientists use weather stations to measure hail, rain and snow amounts which are then mapped using an online reporting portal (https://www.cocorahs.org/). In yet another study, mobile technologies were used to gather precipitation and other data during the Monsoon season in Nepal (Davids et al. 2019). Using the Android based Open Data Kit Collect app, citizen scientists were able to collect thousands of precipitation measurements using low-cost, homemade rain gauges.

The use of citizen scientists to monitor water quality and surface water quantity is also well documented in the literature. For example, citizen scientists have been leveraged to test the presence of bacteria in drinking water in the Netherlands (Brouwer et al. 2018). In this project, citizen scientists used test strips to test for bacteria in water samples collected from their taps. Other studies have used citizen scientists to monitor surface water levels across the globe. These include King Tides (California, United States) (California Coastal Commission https://www.coastal.ca.gov/kingtides/), Crowdwater (global) (Seibert et al. 2019), Crowdhydrology (United States) (Lowry and Fienen 2013), and the Sondu-Miriu River basin project (Kenya) (Weeser et al. 2018).

Although citizen scientists provide an opportunity to collect various types and quantities of data, questions remain about the quality of the collected data (e.g., Tregidgo et al. 2013). This is particularly the case for groundwater where very few articles have been published that have attempted to highlight the trustworthiness of groundwater data collected by citizen scientists (e.g., Lowry and Fienen 2013; Little et al. 2015; Baalbaki et al. 2019). Major impediments to involving citizen scientists in groundwater monitoring projects, particularly those that involve groundwater quantity, include lack of resources to facilitate monitoring programs (e.g., money, time commitment, equipment, monitoring wells, etc.), need for training and oversight of citizen scientists, and uncertainty about the quality of data from citizen scientists (e.g., Lowry and Fienen 2013).

In many places (e.g., North Carolina, United States), cuts to environmental agency budgets have placed significant stresses on the respective parties' abilities to maintain groundwater monitoring networks. Since groundwater is crucial to the economies of communities that depend on these resources, conducting citizen science projects would be beneficial to understanding long-term viability of groundwater resources. The novelty of the present paper is that it (1) focuses on describing the process of enlisting community members in a scientific project to characterize the water table in coastal communities where groundwater plays a large role in sustainable water resources management, and more importantly (2) evaluates the trustworthiness of groundwater data collected by citizen scientists. The objectives of the study are therefore to (1) recruit, train, educate and engage citizen scientists in a groundwater monitoring project, (2) monitor and record groundwater levels using citizen scientists and automated water level loggers, and (3) establish the trustworthiness of data collected by the citizen scientists. To the authors' knowledge, this type of study has not been previously attempted.

Study Area and Hydrogeologic Setting

The study was conducted on Bogue Banks, an approximate 28 km^2 barrier island off the coast of North Carolina (Figure 1). The elevation on Bogue Banks ranges from approximately 1 m below sea-level to 17 m above sea-level. The largest dunes on the island are observed in the south western part of the island, whereas the ground surface in the northern portion of the island generally slopes gently into Bogue Sound (Manda et al. 2015). Lautier (2001) characterized the hydrogeologic framework of the North Carolina Coastal Plain aquifer system as a wedge of formations that dip and thicken to the east. The resulting sediment wedge varies from 30 m thick in the western coastal plain to more than 2400 m thick under Cape Hatteras on top of Paleozoic basement rock (Winner and Coble 1996).

Methodology

Monitoring Stations

A total of 29 monitoring wells were installed on Bogue Banks (Figure 1) to monitor groundwater levels. The wells were installed in the surficial aquifer in different environments to account for differences in topographic features and for accessibility by researchers and citizen scientists. All wells were installed using a "geoprobe" direct push drilling rig following North Carolina State standards for constructing groundwater monitoring wells. Each well consisted of 1-inch (2.54 cm) diameter polyvinyl chloride pipe, with well depths ranging from 2 to 8 m below ground. A Trimble global positioning system unit was used to determine the geographic coordinates of the completed wells. Solinst water level loggers were installed in the monitoring wells and set to record water levels at an interval of every 10 min.

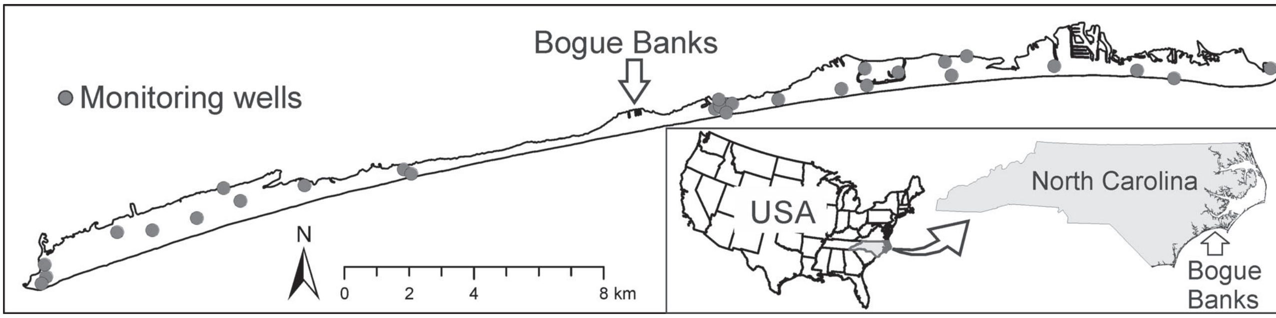

Figure 1. Location of Bogue Banks off the coast of North Carolina.

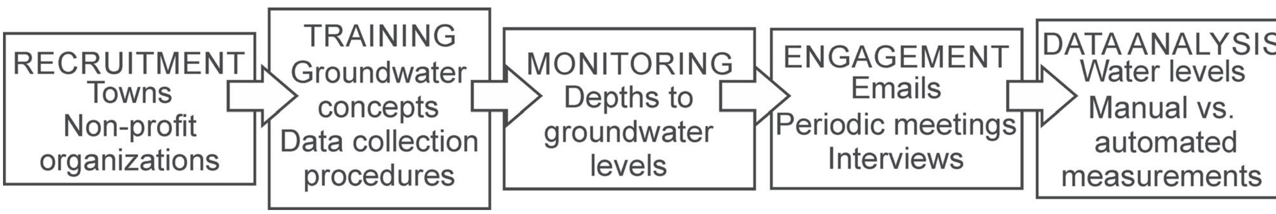

Figure 2. Flow chart illustrating project activities.

Project Activities

The activities that were undertaken in this study to determine the trustworthiness of groundwater data involved the recruitment of participants, training of participants, collection of groundwater data, periodically checking in with the participants, and analyzing the data collected during the study (Figure 2). The following sections describe these activities in greater detail.

Recruitment

The researchers partnered with various entities to recruit citizen scientists to participate in the project. The North Carolina Aquarium at Pine Knoll Shores and the North Carolina Coastal Federation used their vast networks to inform potential participants about the citizen science opportunity. The researchers also held several informational workshops and sessions during various events that were hosted by the nonprofit organizations to advertise the project to broader and diverse audiences. Municipalities on the island were also instrumental in advertising the project through newsletters, emails, and posters. Multiple recruitment efforts were implemented, the first of which was used to recruit seven people to participate in a pilot study in 2015. The results and outcomes of the 10-week pilot study that was conducted (not described here in detail) were then used to inform the approach, design and implementation of the second recruitment effort to officially launch the groundwater monitoring project in 2017. For the project in 2017, 31 people attended an informational session and training workshop at the official launch of the project. Attendees at the launch of the official groundwater monitoring project were informed of the purpose, expectations, processes, benefits, and risks of participating in the groundwater monitoring project (i.e., informed consent). All attendees signed informed consent forms that were approved by the Institutional Review Board at East Carolina University. The attendees then participated in an interactive activity using physical groundwater models to help them understand basic concepts of groundwater flow systems. Thereafter, the attendees participated in an open discussion about the implications of groundwater on stormwater flooding and potable water supply (issues that are important to residents on the island).

Training

Following discussions, the participants went through an indoor training workshop on how to properly access groundwater monitoring wells, and how to effectively use electronic water level meters to correctly measure and record the depth to water in groundwater monitoring wells. The training emphasized (1) the difference between "depth to water level" and "water level elevation," (2) the process for converting from "depth to water level" to "water level elevation" and vice versa, (3) the appropriate units of measurement (e.g., meters vs. feet, and decimal feet vs. feet and inches), and (4) the importance of effective communication between volunteers and researchers. These additional elements of emphasis were made because of feedback and lessons learned during the pilot study. For the final training activity, each attendee was taken to a monitoring well to practice the process of measuring and recording water level data under the keen observation of the researchers. This ensured that the attendees had the confidence to independently collect the appropriate data when the project commenced. Each of the attendees was expected to measure and record water level data from at least one groundwater monitoring well at least once a week (at an agreed time) from February 7, 2017 to April 28, 2017 (an 81-day period). During this period, the researchers engaged with the participants through telephone and email communications, and in-person group discussions.

Monitoring

After the training, each participant was assigned at least one groundwater monitoring well to monitor (number of wells per participant ranged from 1 to 3), a laminated sheet with guidelines on how to monitor groundwater levels, a map of the island showing the well IDs and locations, keys for locks on wells, an electronic water level meter (imperial units, with marks every 1/100 feet), and data sheets on which to record water level data (attributes on data sheets included date, time, and depth to water level from top of well casing). The attendees were also provided with a link to an online portal that they could use to upload their measurements. Initially, the citizen scientists were to collect data synchronously, with each citizen scientist collecting data at 10 AM every Friday for the duration of the project. However, due to differences in schedules, the citizen scientists were provided several options when they could measure and record water levels (e.g., 10 AM Tuesday, 6 PM Thursday, 10 AM Friday, 3 PM Saturday, 5 PM Sunday, etc.). The manual groundwater level measurements recorded by the citizen scientists were compared to the automated groundwater levels recorded using water level loggers to evaluate how well the data collected by the citizen scientists matched the data recorded by the water level loggers. The researchers also periodically collected manual groundwater level measurements to confirm the quality of readings recorded by the automated water level loggers and citizen scientists.

Engagement

Group discussions (held at the beginning, middle and end of the 12-week period) involved discussions of the scientific process, results of analyses, and any challenges encountered during the project. Discussions between researchers and citizen scientists that involved the scientific process focused on testing the hypothesis that a high water table contributes to stormwater flooding on the island. The data that the citizen scientists were to collect were to be used to show when, where and by how much the water table rose above the land surface during the monitoring period. To facilitate the discussions, the researchers first had to create (1) graphs showing how groundwater levels varied with time, (2) graphs showing how precipitation varied with time, and (3) maps showing water table contours on the island at specific times during the monitoring period. Any challenges to (1) understanding hydrologic concepts, and/or (2) completing project tasks were addressed through group discussions and/or other forms of communication. During the project, the researchers periodically communicated with the stakeholders to discuss preliminary results, revise strategies for accomplishing tasks, gather data sheets, and get feedback from the participants. This approach ensured that (1) the citizen scientists were continuously reminded of the importance of their monitoring efforts, and (2) the project activities continued to engage the interests of the citizen scientists.

Data Analysis

In addition to descriptive statistics, several methods were used to assess the trustworthiness (i.e., validity and reliability) of the water level measurements collected by citizen scientists (here, validity is defined as the extent to which a quantity is accurately measured, whereas reliability relates to the consistency of a measure; Heale and Twycross 2015). First, visual comparison was used to evaluate how time series data from citizen scientists aligned with time series data from water level loggers. Then, the Nash-Sutcliffe (NS) coefficient of efficiency (Nash and Sutcliffe 1970) was used to test the goodness of fit of the two types of data (*validity*). The NS coefficient of efficiency is commonly used in hydrological studies to assess the goodness of fit between simulated data and observed data (Anderson et al. 2015). The Bland-Altman method was also used to evaluate the *validity* of measurements by assessing agreement between measurements collected by citizen scientists and the automated water level loggers (Bland and Altman 1986, 1999). The intraclass correlation coefficient (ICC) (Shrout and Fleiss 1979; McGraw and Wong 1996) and the concordance correlation coefficient (CCC) (Lin 1989, 2000) were used to assess the *reliability* of measurements of water levels collected by citizen scientists. These methods are described in more detail in the Supporting Information.

Results

A total of 28 citizen scientists ultimately participated in the project; the participants were mostly white (95% white), retirees (~50%), and well educated (75% had bachelor's degrees) (Grace-McCaskey et al. 2019). However, of the 28, only 21 completed the project as was requested, and only 12 participated in the final meeting. As a result, a total of 35 sets of time series data with 455 unique water level measurements were available for further analysis. Plots of time series data from citizen scientists and automated water level loggers (e.g., Figure 3) indicate that in general, the data collected by the citizen scientists matched the data from the automated water level loggers well, particularly after a quality control procedure was implemented (e.g., visually inspecting the time series data and then removing any spurious data points). Descriptive statistics that indicate the goodness of fit of data from citizen scientists and automated water level loggers reveal small errors and standard deviations. The results of the Bland Altman method indicate that 16 of the 35 sets of data (i.e., 45%) that were generated by the citizen scientists are considered valid. Even though a little less than half of the data sets are considered valid, close inspection of the results indicates that at least 80% of all measurements in each data set fall within the 95% confidence intervals (Supporting Information). Additionally, the NS coefficient of efficiency for almost all datasets is greater than 0.85 and close to 1, indicating very good

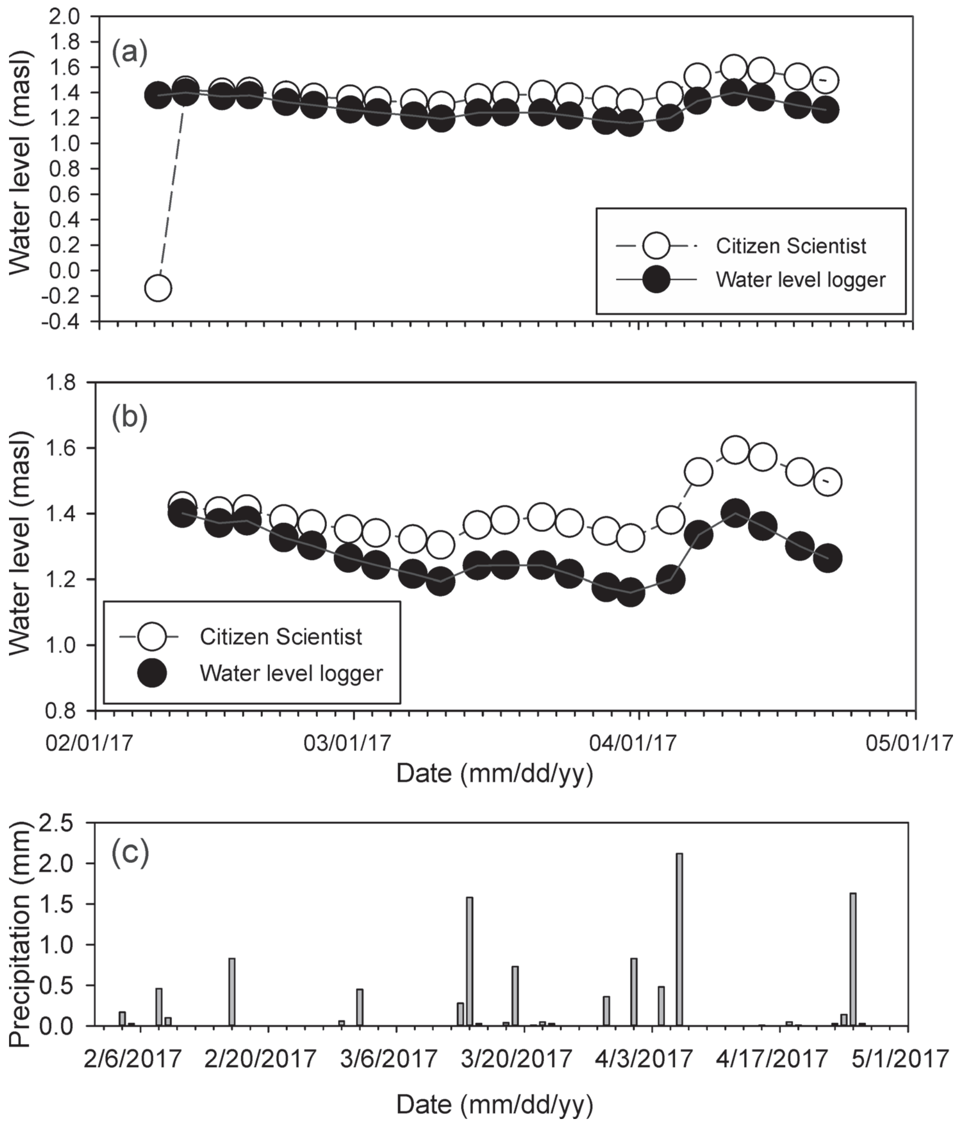

Figure 3. Time series of groundwater levels from citizen scientists and automated water level loggers prequality control (a), and post quality control (b). Bar graph of precipitation (c). Manual measurements collected by the researchers indicated that the data from the logger did not match the data recorded by the researchers. This observation and the fact that the deviation between logger derived and citizen scientist derived data consistently increases suggests that the instrument experienced data drift.

fit (i.e., validity) between water levels recorded by citizen scientists and automated water level loggers. A large proportion of the data sets (~86%) have ICC values in the range 0.85 to 1.0 signifying excellent reliability of data collected by citizen scientists. The CCC results follow a similar pattern as the ICC results: 88% of the data sets have CCC values greater than 0.74.

The validity and reliability of multiple data sets collected by a single participant were also evaluated. The results show that there are six citizen scientists that recorded water level measurements from more than one well (for a total of 15 data sets): three citizen scientists recorded water levels from two wells, and three other citizen scientists recorded water levels from three wells (Supporting Information). With respect to validity, the results from the goodness-of-fit analysis indicate that the data collected by each of the six citizen scientists are valid with NS coefficients that are greater than 0.8. The results also indicate that, in general, the reliability of the measurements from each of the six citizen scientists is excellent or substantial.

The mean error can be used as a measure of bias because unlike the root mean square error or the mean absolute error, the mean error can be either positive or negative indicating over- or underestimation of a measurement. If we consider the mean error from the six citizen scientists, we can evaluate how consistent each citizen scientist was in measuring water levels from different groundwater monitoring wells. Generally, the mean error results show that there were cases that an individual citizen scientist would overestimate the measurements in one well but underestimate the measurements in another well. Interestingly, most of the time series results show that when a citizen scientist underestimated a water level measurement, they consistently underestimated other measurements for that well, and vice versa. The magnitudes of these deviations were not greater than ± 0.05 m. The reader is referred to the Supporting Information for multiple tables and graphs that accompany the results reported in this section.

Discussion

The low number of cases where data sets were deemed not reliable (<3) or not valid (<3) suggests that most of the data collected by the citizen scientists are trustworthy. Some of the issues that are typically raised when considering the usefulness of citizen scientist data involve quality control and assurance. As has been shown in this study, with proper training and a mechanism for evaluating data (e.g., online portal validation), citizen scientists can do a reasonable job in collecting groundwater level data that is valid and reliable.

Although the workshop, training session and online portal validation helped to reduce errors, there were a few mistakes that were discovered when the data retrieved from the online portal were compared to the data that were on the data sheets. This quality control process was used by the researchers to fix any entries that were incorrectly entered by the citizen scientists on the online portal. Some of the mistakes included entering wrong dates, or switching digits during the transfer of data from the data sheet to the online portal (here, the researchers had greater faith in the data on the data sheet than on the online portal). In the future, other researchers could consider asking volunteers to submit their measurements using software such as Social.Water (Fienen and Lowry 2012) that have a mechanism for submitting data using SMS.

This study was part of a larger research project that was designed to ... "(1) recruit, train, educate and engage citizen scientists to measure and record hydrologic data, (2) monitor groundwater levels and surface water levels, (3) determine the validity and reliability of hydrologic data collected by citizen scientists, and (4) evaluate the perceptions of citizen scientists participating in the project" (Grace-McCaskey et al. 2019; Etheridge et al. 2020). Since the objective of the current study was to highlight (1), (2), and (3), other articles have been published by the authors that report in greater detail the perceptions of citizen scientists and the lessons learned from the broader research experience (Grace-McCaskey et al. 2019, Etheridge et al. 2020). For completeness and context, we incorporate some of the insights from those previous studies into this study to better understand the results and outcomes of the current study.

One of the major outcomes of the broader study is that while the data collected by citizen scientists may be trustworthy, there was a significant amount of time that was invested by the researchers into the project. Not including the time spent on designing the project and analyzing the data that were subsequently collected during the study, the researchers spent countless hours *nurturing relationships* with collaborating partners (e.g., town officials, representatives from nonprofit organizations, etc.). These relationships were key for getting buy-in from leaders of municipalities and organizations that enabled access to facilities and resources (e.g., water managers for the towns), members of organizations, and residents of towns. Additionally, and more importantly, these relationships ensured that many potential participants were made aware of the opportunity to participate in a citizen science project. Having large numbers of participants is crucial for (1) covering a large spatial extent of the study area, and (2) performing robust statistical tests for determining whether results are significant or not.

Once relationships were established, the researchers spent many hours *recruiting volunteers* for the project. Researchers took advantage of many opportunities to drive to the field area (about a 1.5 h drive one-way) to engage with potential volunteers at open house events, annual meetings of organizations and other special "request for citizen scientists" events (see example of email/flyer in Supporting Information).

In addition to the launch meeting where the researchers provided *training and education* to the citizen scientists, there was also considerable time spent by the researchers in maintaining the interest of the citizen scientists in the project. This type of *active engagement* involved many hours of sending emails and making phone calls to the citizen scientists. In Etheridge et al.'s (2020) alternative cost comparison (i.e., traditional method versus public participation), the authors estimated that the Principal Investigator probably spent ~44 h over the 3-month period for the project. This analysis neither accounts for other team members' involvement, nor does it consider the time spent nurturing relationships, thus the total amount of time provided in Etheridge et al. (2020) is an underestimate of the time spent on the project. Considering these insights, researchers that are thinking about undertaking citizen projects that involve groundwater should seriously consider their time commitments.

It should be noted, however, that citizen science is also an important vehicle for involving the public in scientific studies and thus, has the potential to increase the scientific knowledge of participants (Grace-McCaskey et al. 2019). The benefits that may arise from citizen science projects may therefore transcend matters of cost, particularly where the area of interest is very big so much so that costs of traditional methods far exceed those of public participation in science.

Conclusions

This study is the first to quantitatively evaluate the trustworthiness of groundwater level data collected by citizen scientists. Results of this study demonstrate that environmental data collected by citizen scientists can be trustworthy if certain protocols are followed during the citizen science project. This study reveals that positive outcomes (e.g., trustworthy data) from citizen science projects require a robust pool of participants (achieved through *nurturing of relationships* and *effective recruitment*) that know how to effectively collect data (achieved through *training and education*) and are motivated for the duration of the study (achieved through *active engagement*). Using approaches such as those outlined here, the broader community is likely to benefit from citizen science activities by having access to high-quality, long-term, and widely distributed groundwater level data that may be available to researchers and other end users (e.g., water managers). It is noted, however, that running effective citizen science projects requires significant investments of time and energy. Thus, other people that may want to involve the public in citizen science projects that focus on groundwater would need to consider their time commitments very carefully if they are to run a successful citizen science project.

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Authors' Note

The authors do not have any conflicts of interest or financial disclosures to report.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Appendix S1. (1) Detailed descriptions of methods used to generate results of the study, (2) results in tabular format from the study, (3) different types of graphs that were generated during the course of the project, and (4) an example of a flyer/email that was used to recruit participants.

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