# Citizen science tools for engaged research: Water quality monitoring in remote communities

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Remote areas that lack conventional water-provisioning infrastructure often rely on rainwater harvesting, rivers, pans, reservoirs and borehole-extracted water to meet domestic water requirements. These water sources often have poor microbial quality and chemical composition, the quality of which is not routinely monitored. This study explored citizen science as a tool for Engaged Research and Responsible Research and Innovation, detailing the co-creation of a sustained community-based water quality monitoring program in collaboration with communities in villages in Amakhala Game Reserve (Eastern Cape, South Africa). Without access to other water sources, participants predominantly used rainwater for drinking and cooking (80%), while borehole water was mainly used for cleaning and gardening due to its salty or bitter taste. A hydrogen sulfide ($H_2S$) water testing kit was used by the citizen scientists to monitor the water quality. The $H_2S$ kits were effective in estimating bacterial contamination, showing a proportional relationship with Colilert® test results conducted in a laboratory. The alignment observed between community-based monitoring results and those derived from scientist-led testing underscores the value of data produced through citizen science initiatives. Sustained participant engagement throughout this research reflected a sense of community empowerment through access to tools that inform their decision-making around water use and treatment as well as investment in the research, indicative of the perceived relevance of the research to community interests. This integration of transdisciplinary data sources holds promise for informing evidence-based decision-making processes, facilitating more effective and contextually informed water management strategies that value and integrate community perspectives alongside scientific insights.

**Significance:**

Drawing on the principles of Engaged Research and Responsible Research and Innovation, we applied citizen science tools to engage researchers and communities in the co-development of a water quality monitoring program. In addressing a specific area of concern, raised by the remotely situated community around the need for knowing their water quality, the project successfully trained communities in applying water testing tools and fostered agency in decision-making around water treatment. Combined with continuous feedback and communication loops, a high rate of continuity was sustained among the participants.

## Introduction

Access to safe drinking water remains a global challenge, exposing communities to waterborne diseases and their attendant consequences on health. Reliance on alternative water sources such as rivers, streams, pans, dams and reservoirs as well as rainwater harvesting and borehole water in rural regions is a common practice already employed in different African countries, including South Africa.[1,2] South Africa specifically has poor water management systems while also experiencing low rainfall. These water sources often have poor quality when considering either microbial presence and/or adverse chemical compositions.[3] Many rural communities in South Africa are therefore reliant on unsafe, untreated, water sources for drinking purposes, risking exposure to waterborne diseases and other adverse health effects.[4] Community knowledge and understanding of water quality and treatment is crucial in the prevention of waterborne disease outbreaks. Lack of access to water quality information and to information on alternative methods of treating water for the community has created a situation of epistemic injustice.[5] The ability of the community to act upon the water quality problem is dependent on understanding specific aspects of water quality and their attendant health implications. Citizen science approaches may offer an opportunity for community-based water quality monitoring to address shortcomings in the routine monitoring of water quality.

Citizen science, as a tool, engages non-scientists in scientific research and processes, encouraging communities to contribute to – or address issues using – science-based approaches.[6,7] Different conceptions of citizen science denote these as being either (i) community-led, where communities identify problems that can be addressed through scientific methods and engage with various stakeholders for problem-solving[8,9], or more frequently, (ii) scientist-led, where scientists invite communities to engage in specific research programmes. For the latter, several examples exist in the literature and in publicly accessible databases: many of these are data-gathering citizen scientist activities that continue to provide valuable information and monitoring in scientific areas that include astronomy, alien plant eradication, wildlife and water monitoring, among others. The inherent capability of involving the broader public in 'hands-on' scientific activities positions citizen science as a pivotal instrument, not only for fostering a deeper appreciation and understanding of scientific concepts but also bolstering science education and literacy within diverse communities.[10,11] Kruger and Shannon[12] also note the potential it holds for democratising science by involving citizens as researchers; the extent to which democratisation occurs arguably being determined by the extent of involvement that citizens have in shaping the research.

Substantial scope exists for meaningful engagement of communities in scientific research, with the extent of engagement determined by both the nature of the engagement and its potential outcomes. Communities having a role in shaping research is advocated for in South Africa's Science Engagement Framework, wherein Engaged

Research refers broadly to engagements between researchers, communities and other stakeholders, at any stage of the research process, and their involvement in the research outcomes. This approach is informed by: "the values of contemporary, post-apartheid South Africa, most specifically the imperative of empowering its citizens to engage with processes and issues that affect them"[13]. This strategy echoes the European Union's Responsible Research and Innovation (RRI) framework with some of its core foci centred on engagement with the public, gender equality, ethics and democratisation of science. One of the defining features of RRI is that it advocates for engagement between scientists and communities throughout all stages of the research and innovation process, ideally from the outset.[14] One of the challenges of RRI is putting this into practise in a way that sustains the engagement and the active participation of impacted communities. While citizen science is often viewed as separate from engaged research frameworks, it offers a set of tools to sustain active community engagement and promote an understanding of science.

This paper offers a case study exploring how citizen science approaches can be embedded into engaged research and RRI frameworks as an approach, not only involving communities in shaping research but also facilitating co-creation between scientists and communities. This study aimed to explore citizen science as a tool that draws on the principles of RRI and Engaged Research to engage communities as citizen scientists. Applying a community-based monitoring citizen science approach, communities of Amakhala and researchers sought to co-develop a community-based programme focusing on monitoring rainwater and borehole water quality in these villages.

In the research, it was hypothesised that the use of $H_2S$ testing kits by citizen scientists would provide an accessible tool for communities to monitor microbial quality of water and that this would correlate with water quality results using IDEXX Colilert® tests conducted in a water quality testing laboratory.

## Site of the study

The Amakhala Game Reserve is a private game reserve in a remote area between the cities of Gqeberha and Makhanda, in the Eastern Cape Province of South Africa.[15,16] The game reserve includes seven villages that are home to approximately 200 adults and 80 children.[16] Five of these villages were involved in this study: Leeuwenbosch, Kraaibos, Carnarvon Dale, Brentwood and Beacon Hill (Figure 1). These communities rely on rainwater tanks and borehole-supplied water, the quality of which is not formally monitored.

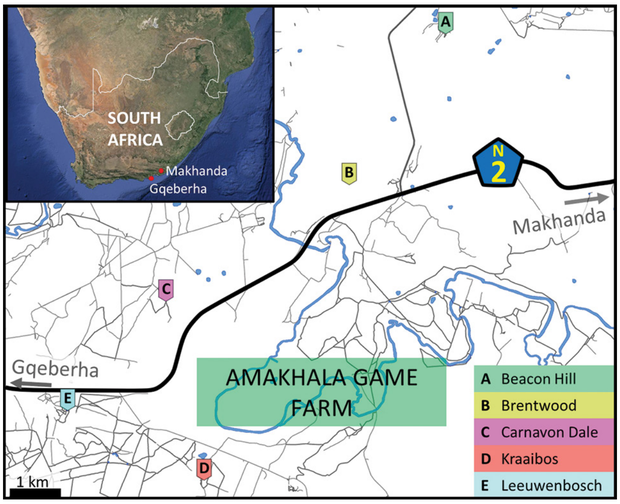
## Methods

This study built on a longstanding relationship – an ongoing partnership between the broader Amakhala community and Rhodes University's Community Engagement Division started in 2017, centred on land reform and reconstitution strategies – between community partners and the researcher. This study occurs as part of several other community engagement initiatives and studies that developed from this relationship.

The methodological approach followed four phases, as graphically depicted in Figure 2.

### The exploratory phase

This phase commenced with informal discussions held between an existing research team within Rhodes University's Community Engagement Centre, who were engaging communities in the Amakhala Game Reserve on health-related concerns. During the finalisation of that research, informal discussions were held with community members. Small group discussions were held at three sites in Amakhala (Kraaibos, Reed Valley and Leeuwenbosch) in 2019. During these sessions, researchers asked about other challenges that community members experienced due to their remoteness. Community members highlighted concerns about the quality of their drinking water and expressed an interest in knowing the quality of their water. This was consistent with other concerns raised by villagers in the 2017 Community Report, which highlighted the need for improved water supply, access to electricity and better housing conditions.



*Source: Maps were generated using:* https://snazzymaps.com/build-a-map *(all styles are licensed under a Creative Commons licence)*

**Figure 1:** Map detailing the location of the Amakhala villages in which community participants in this study resided, showing their location relative to local roads (grey), the N2 national route (black) and local water sources (blue). Map quadrant from –33.4617; 26.0548 (top-left) to –33.5534; 26.1976 (bottom-right). Top-right inset: map of South Africa, indicating the two major cities closest to the Amakhala Game Farm; Amakhala is approximately mid-way between these two points.

### Defining the scope of the research

Subsequently, a survey was conducted with communities in the five villages comprising the study site (Figure 1), to explore the communities' concerns about water quality and to establish their interest in monitoring the quality of their water. At the time of the survey, the five identified villages consisted of 47 households. All the households in these villages were invited to participate; 29 of the households, each represented by one person, agreed to participate and were interviewed as part of the study. The main cited reason for non-participation was non-availability due to work or not being available for the whole duration of the study. Survey questionnaires (Supplementary material) were conducted in person – either individually or in small groups of up to three participants – across the five villages. Questionnaires were provided in both English and isiXhosa and were administered using the Kobo Toolbox.[17]

The Kobo Toolbox[17] is software used to collect, analyse and manage data for surveys, monitoring, evaluation and research. Researchers worked with individual community members on completing the questionnaire, inputting the responses provided into the Kobo Toolbox application. As the participants responded to each question, the researcher typed out the answer and read it back to the participant to confirm correct capture of the response.

### Developing the citizen science programme

Based on the insights gathered from both the survey and through informal conversations between researchers and communities, a citizen science community-based water quality monitoring programme was developed. This design aimed to engage the Amakhala community members as citizen scientists, empowering them to actively monitor the quality of their water. The programme entailed four stages: (1) identifying the water quality indicators to be tested and identifying existing tools for said indicators; (2) identifying participants interested in becoming citizen scientists and providing training in the use of testing tools and interpretation of results; (3) citizen scientists monitoring water quality using the $H_2S$ kits over an 18-week period during which (a) communities assessed their water's quality through weekly sampling and (b) periodic paired sampling was performed by researchers to conduct comparative laboratory testing of water quality using Colilert® testing in a laboratory;

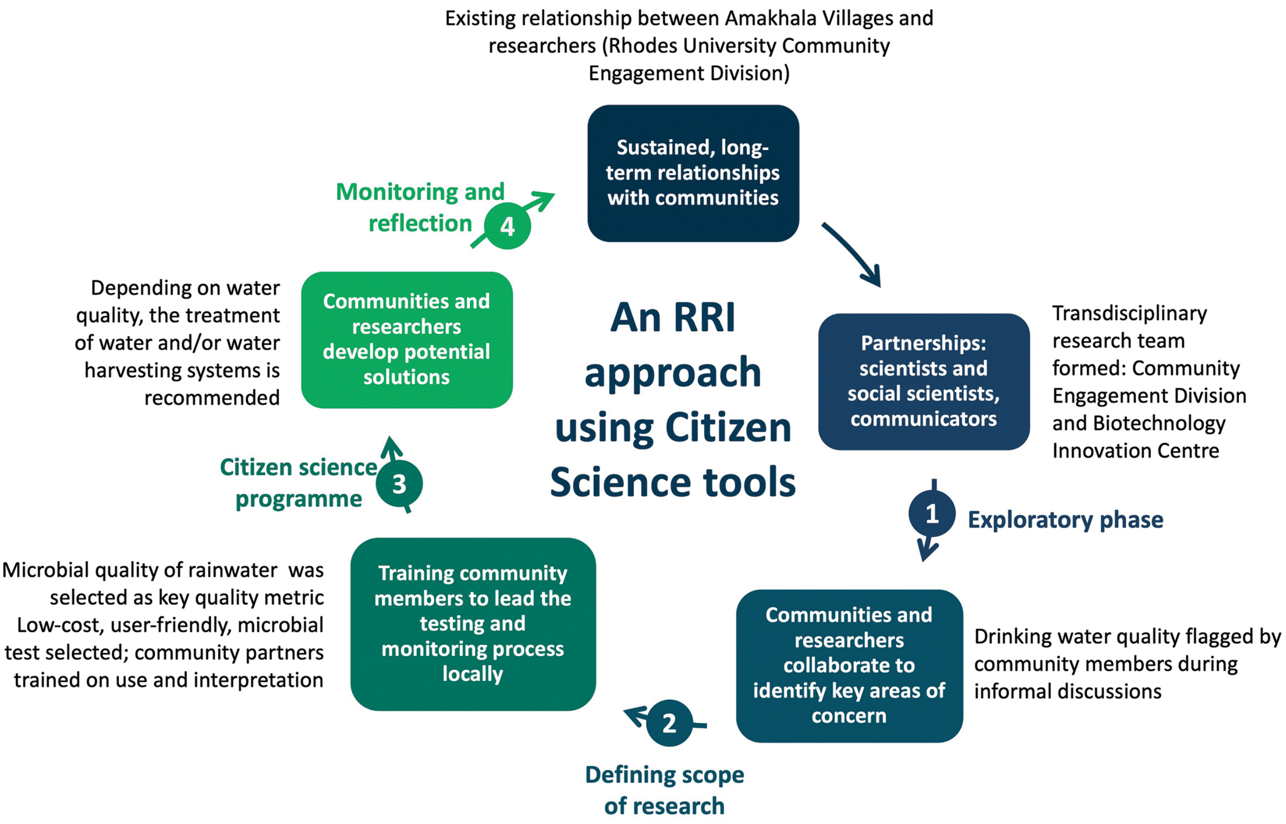


**Figure 2:** Citizen science tools integrated into the current RRI/Engaged Research Study, centred around developing community-level water quality monitoring tools.

and 4) weekly reflection on results obtained and discussions between scientists and communities.

### Language

In the engagements with the community, isiXhosa (an indigenous language of the Eastern Cape Province of South Africa) was used. Code switching between isiXhosa and English for some scientific terms was important to ensure that some concepts and methods were understood by the citizen science participants. The citizen scientists were requested to use the language that they were comfortable using during workshop discussions and when completing the questionnaires. Mji and Makgato[18] support the use of code switching by arguing that language transcends both direct and indirect influences in science education.

a. **$H_2S$ test kit training**

The hydrogen sulfide ($H_2S$) test kit for the detection of coliform bacteria in water is a microbial testing approach used in several studies[19-22], using purpose-built low-cost $H_2S$ testing kits. Test kits were constructed following reported protocols.[19]

A demonstration of the use of the $H_2S$ testing kit was carried out with community members, in groups of up to three people. Each person was provided with five test kits and was trained on the use of the kit under the guidance of the researcher. A brochure detailing the $H_2S$ test kit methods and the interpretation of results was developed and provided to each citizen scientist, in both English and isiXhosa (Supplementary material). Each brochure included a description of possible water treatments that communities could follow when the tests indicated the presence of microbial contaminants.

b. **$H_2S$ test kit validation**

To ensure the scientific validity and authenticity of a citizen science project, it is essential to adhere to the universal principles of science studies, as articulated by Silvertown.[23] These principles emphasise the validation of the data collected and the standardisation of data collection methods. Furthermore, it's crucial to provide citizen scientists with feedback on their contributions, serving to acknowledge and affirm their role in the project.

To validate the $H_2S$ test kit as a tool for use by the community in Amakhala to effectively monitor water for bacterial contamination, samples of rainwater were also collected by the researcher and further analysed on the same day for the presence of total coliforms using standard Colilert® assays[24]; this is discussed in greater detail below.

### *Monitoring the citizen science project and reflection*

Evaluating the success of citizen science projects requires a comprehensive approach due to the diverse objectives and outcomes they encompass.[25,26] Key metrics include tracking both the volume and diversity of participation; ensuring the accuracy, precision and usability of the collected data; determining whether an increase in participants' knowledge and skills occurs.

The citizen scientists of the Amakhala communities monitored the microbial water quality of their water sources for 18 weeks. At the beginning of each week, each citizen scientist received five $H_2S$ water testing kits. They used all five kits by testing a single water sample once a week, measuring coliform contamination. Following 72 hours' incubation, participants recorded the number of issued $H_2S$ water testing kits (out of a total of 5) that were positive. Placing the sealed test bottles in a dark area at room temperature, typically between 25 °C and 37 °C allowed for incubation of the samples. Temperatures lower than this interval could affect the incubation of the $H_2S$-producing bacteria.

Paired water sampling was conducted periodically (Weeks 1, 7 and 18), using Colilert® testing conducted by the researchers. The samples for Colilert® testing were collected using 1-L Schott bottles and stored on ice for transportation; samples were processed within 12 hours of sampling.[22] These samples were collected at the same time and place as the $H_2S$ sampling sites.

Throughout the 18-week monitoring phase, weekly informal meetings and discussions were held between researchers and the community members serving as citizen scientists to facilitate the interpretation of results and stimulate conversations on appropriate water treatment techniques. These interactions served as a platform for ongoing engagement, knowledge exchange and collaborative problem-solving between the researchers and community members. The discussions also helped identify the scope for future research, especially with respect to the limitations of the test kit and treatment options.

### Data analysis

Quantitative information extracted from the questionnaires' answers, from the $H_2S$ kits validation and the responses of the citizen scientists' water monitoring using the $H_2S$ kits were evaluated statistically, using *R* (*v* 4.3.1), using the *ggplot2* package to generate graphical summaries of this information. Specific inferential statistical tests used to evaluate significant differences between samples can be found within the captions for these summaries.

## Results

### *Exploratory survey*

During the exploratory phase, the researchers further probed which specific aspects were of greatest concern: knowing their water's quality or developing tools to treat water. Community members highlighted that a preference for first knowing the quality of their drinking water was of specific importance, stating that having access to the information would allow them to make determinations as to its safety for consumption. These informal discussions shaped the nature of the research direction and provided the scope for the survey questionnaire (Supplementary material) and future follow-up site visits.

### *Findings from surveys and site-visit observations*

A total of 29 community members agreed to participate in the survey, each as representatives of their households (ranging between 1 and 10 members) (Figure 3). The sections below summarise the demographic profile of the study's participants (Figure 3) and some of the pertinent responses captured by the survey.

Household sizes varied considerably within the cohort, from members living alone to those living in 10-member households. Larger households were noted among the participants from Brentwood (with a median household size of seven), compared to those of Carnarvon Dale (all respondents indicating that they lived alone) or Leeuwenbosch (median household size of two) (Figure 3A). Larger household sizes were of specific relevance as an indication of an increased reliance on the available water sources. Comparing participants' age and gender (Figure 3B) indicated that significantly more female than male participants formed the cohort within this study: 72% of participants were female. The participants were predominantly aged between 30 and 55 years, with a median age of 39. No significant difference between the distribution of ages between genders was noted in this study.

### *Water demand and supply*

All participants indicated that they accessed both stored rainwater and borehole-extracted water to meet their daily water requirements. Given the location of the surveyed area, being situated in a nature reserve, the communities did not indicate river water as an accessible source of water for them.

The borehole water sources at the Amakhala villages were provisioned by the managers of the Amakhala Game Reserve. These were accessible in all the villages at Amakhala: some villages have outlets/taps installed in household yards; in others, borehole water is temporarily stored in a communal water tank.

The majority of community members among the villages of Amakhala collect rainwater from their rooftops. However, due to the high cost of conventional rainwater tanks, 68% of the households in Amakhala use conventional water storage tanks, while others use alternative containers for collecting water (Figure 4).

There were some significant differences between the purposes of borehole and harvested rainwater used by the participants (Figure 5).

As illustrated in Figure 5, participants highlighted that the activities they were most likely to use rainwater for in their households are for drinking (with significantly more participants indicating that they used rainwater than boreholes to meet this need) and to meet cooking requirements. Of the 55 responses captured for the uses of rainwater, 44 were for these two specific uses, that is, 80% of the total use of rainwater.

Conversely, borehole water was used by the participants predominantly for cleaning purposes (laundry and dishwashing), as well as for

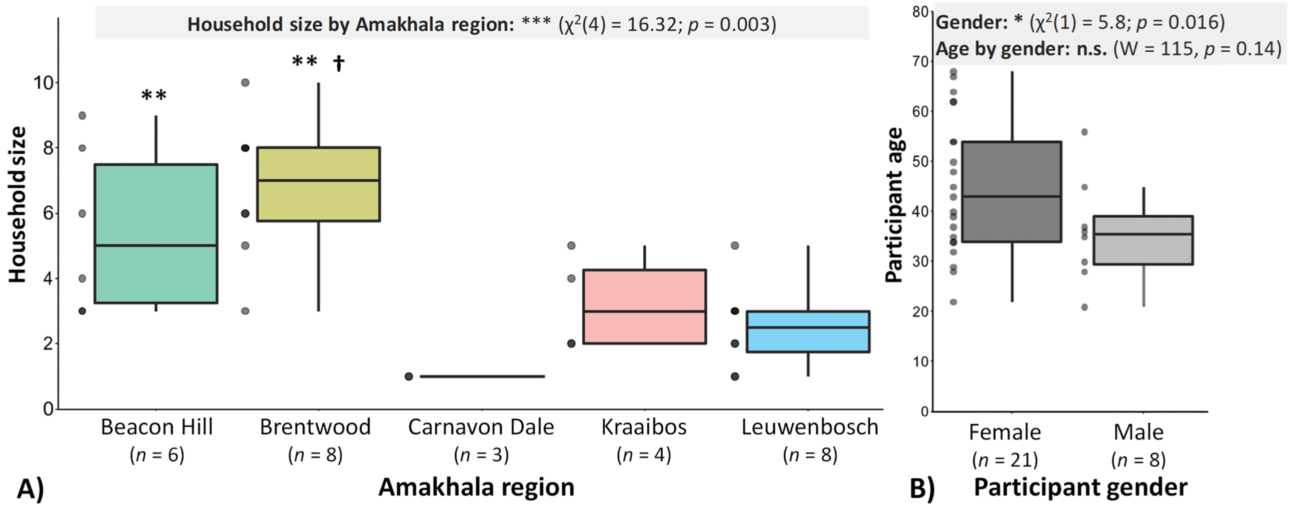


**Figure 3:** Summary of demographic statistics of the composition of the citizen scientist participants. **(A)** Distribution of the household sizes of the participants, compared to the regions of Amakhala in which they reside. The distribution of the participant numbers was not found to differ significantly by their residential region (Fisher's exact test; $p = 0.784$). **Annotations:** Inset text shows results from Kruskal–Wallis testing for significant differences between the medians of samples. ** - significant difference in sample median, compared to Carnarvon Dale sample; † - significant difference in sample median, compared to Leeuwenbosch sample. Significantly different samples identified using Dunn's test, modified using the Benjamini–Hochberg procedure ($p \leq 0.02$). **(B)** Comparison of the ages and genders provided by participants. **Annotations:** Inset text show comparison of the proportion of the respondents' gender distribution and the comparison of the distributions of age by gender.

gardening/irrigation. The majority of respondents (86%) identified that the borehole water was salty or bitter, making it unsuitable for cooking and drinking. No filtration systems were noted on the borehole water accessed by surveyed participants.

**Figure 4:** Various methods of rainwater harvesting employed by participants in the Amakhala region.

Most (66%) of participants indicated that the quantity of water that they receive is insufficient for their household's requirements. Participants highlighted a lack of sufficient rainwater, due to the variability of rainfall in the region as reported elsewhere.[27]

### *Water source treatments by citizen scientists*

Of the 28 participants responding to questions regarding water treatment, 15 (54% of respondents) reported that they do not treat the water prior to drinking it. Given the large proportion of respondents who identified rainwater as being their source of drinking water, many of the answers given related to treatment of rainwater.

Participants who treated their water often used a variety of methods. Drinking water was treated by the cohort by straining/filtering the water ($n = 6$); boiling ($n = 3$), chlorination ($n = 2$); allowing sediment to settle ($n = 2$); placing water in a fridge for a period of time ($n = 2$). One participant added small amounts of paraffin to tanks and waited 3 days before drinking.

Boiling and chlorination are widely recognised as effective means of treating water for safe consumption.[28] However, despite their efficacy, most participants do not treat their water using these methods.[29] This discrepancy can be attributed to various factors, including increased trust in alternative sources like rainwater[30] and the cost implications of treating water in these ways[9,31]. Additionally, contamination of the water by participants was identified by the presence of visible organisms and debris: worms ($n = 5$), insects ($n = 2$), sand and mud ($n = 2$), and leaves ($n = 1$). None of the participants' rainwater harvesting systems had filtration devices installed (Figure 4); this may explain why these contaminants were evident in rainwater supplies and why filtration and/or sedimentation of the rainwater were the most-common treatment options among the cohort.

Given the prevalent use of rainwater as a main drinking source, and the noted microbial health risks associated with its usage, estimation of microbial contamination was selected as the main quality parameter to be evaluated. A low-cost means of measuring this already reported on by the researchers[19] was selected.

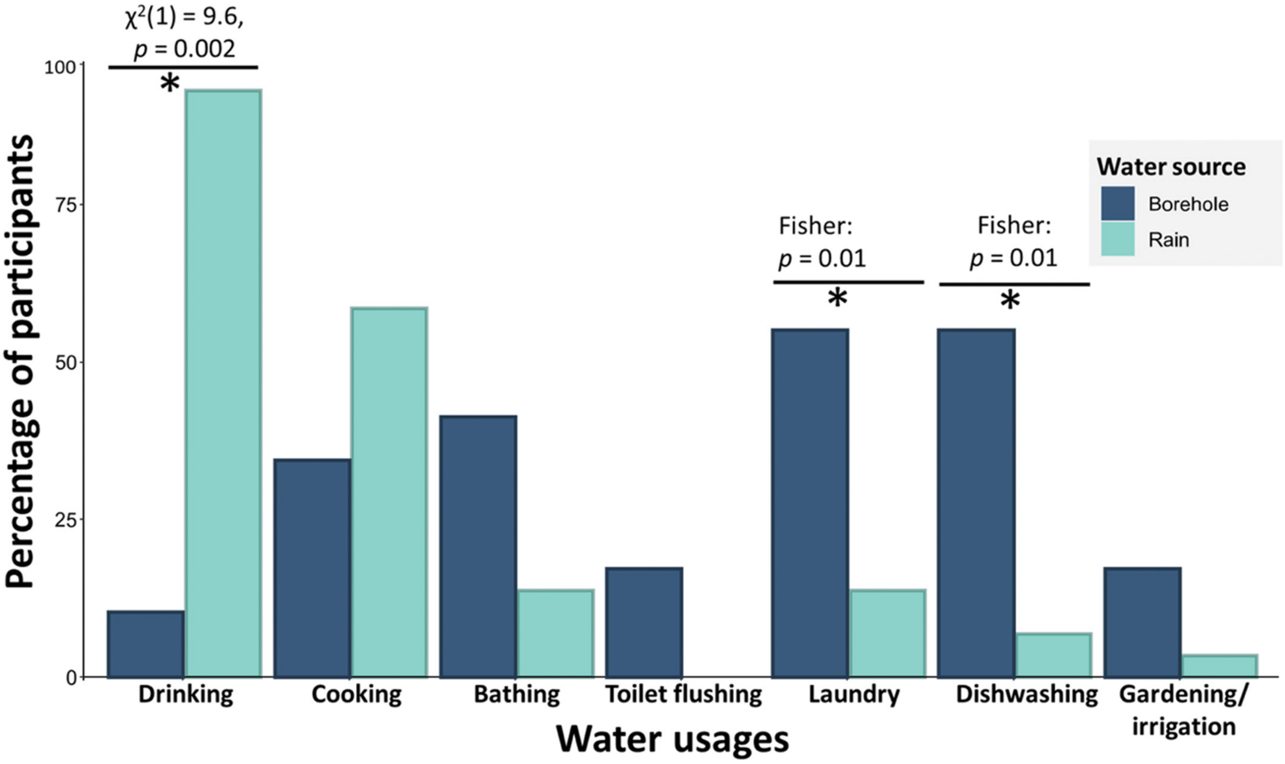


**Figure 5:** Responses to questionnaire sections discussing differences in the usage of water by the participants, based on the source of the water (borehole and harvested rainwater). **Annotations:** Individual tests on the frequency at which a specific water source showed a significantly higher extent of usage are annotated. Depending on the composition of the samples, either Fisher's exact test (for samples with $n < 5$) or chi-squared tests are annotated.

### *Evaluation of the $H_2S$ testing results by citizen scientists*

When asked whether they were interested in testing their water supplies, all participants expressed that they would like to. As a result, all participants received training during the individual village workshops.

Each citizen scientist recorded their test results in a supplied booklet. Results were transcribed and translated using the traffic light system (Table 1) developed to communicate the results obtained from $H_2S$ kits in a user-friendly manner.[19]

The traffic light system (Table 1) interprets the number of test kits into a colour-coded recommendation list: Green (0 positive kit results) indicates water with a low microbial load that is safe to drink: Orange (1–4 positives) indicates water that might contain faecal contamination and needs treatment before drinking, that is, boiling; Red (5 positives) indicates water that is unsafe to drink without extensive treatment.[19] Boiling was recommended as a treatment strategy, as it was effective, low-cost and geographically accessible. If a Red result was obtained, researchers discussed additional water treatment strategies.

The findings of paired water samples jointly analysed by the citizen scientists (using the $H_2S$ kits) and by researchers (using the Colilert® detection method under laboratory conditions) are compared in Figure 6. A total of 84 samples, from both rain and borehole water, were obtained and analysed in parallel. The Colilert® system has two separate tests that estimate total coliform bacteria (including *Escherichia coli*) and *E. coli* levels in water samples, while the $H_2S$ test is a broad coliform indicator (including *E. coli*).[30,32] Therefore, the responses of the total coliform counts obtained by the Colilert® system are compared to $H_2S$ responses.

**Table 1:** Interpretation of $H_2S$ kit test responses using the traffic light system[19]

| Number of positive $H_2S$ kits | Colour representation | Interpretation of water quality |
|---|---|---|
| 0 | Green | Safe to drink. |
| 1 to 4 | Orange | Water requires further treatment (boiling) before consumption. |
| 5 | Red | Do not drink! Report to the councillor. |

In general, paired testing of the water samples indicated that the $H_2S$ kits provided an accurate estimation of the bacterial contamination of the water samples (Figure 6). A proportional relationship between the number of positive $H_2S$ kit responses per test and the total coliform estimates obtained by the laboratory-based Colilert® system is evident. In particular, water samples producing three or more positive $H_2S$ responses had significantly higher bacterial estimates than those producing two or fewer $H_2S$ responses (* annotation, Figure 6).

As Colilert® responses measure the most-probable number (MPN) of metabolically active cells, direct comparison between the results obtained by this method and those required by national water-quality guidelines (which measure bacterial presence as colony-forming units (CFUs)) is difficult; generally, MPN provides a higher estimate of cell numbers compared to CFU.[33] Therefore, similar to other studies[30,34], we distinguish between water samples that are of intermediate-risk ($<10$ MPN/100 mL) and those that are high-risk ($\geq 10$ MPN/100 mL) when comparing the risk estimated by the $H_2S$ kits and that determined by the laboratory-based Colilert® measurement in Figure 6.

False-positive and false-negative responses were based on the above risk-based definition. A total of 8 samples of the 84 produced no positive $H_2S$ kit responses, while 76 produced at least one positive $H_2S$ kit result. False-positive samples generated at least one positive $H_2S$ kit result per test but also produced Colilert® measurements of $<10$ MPN/100 mL; conversely, false-negative samples produced Colilert® measurements of $\geq 10$ MPN/100 mL, but the $H_2S$ kits by citizen scientists failed to generate detectable signal. In this study, the false-negative and false-positive rates estimated by this study are 25% and 8%, respectively. This provided a calculated sensitivity, that is, Equation 1:

$$\frac{100 \times \mathit{true\,positives}}{\mathit{true\,positives} + \mathit{false\,negatives}} = \frac{100 \times 66}{66 + 2} \qquad \text{Equation 1}$$

and specificity, that is, Equation 2:

$$\frac{100 \times \mathit{true\,negatives}}{\mathit{true\,negatives} + \mathit{false\,positives}} = \frac{100 \times 6}{6 + 10} \qquad \text{Equation 2}$$

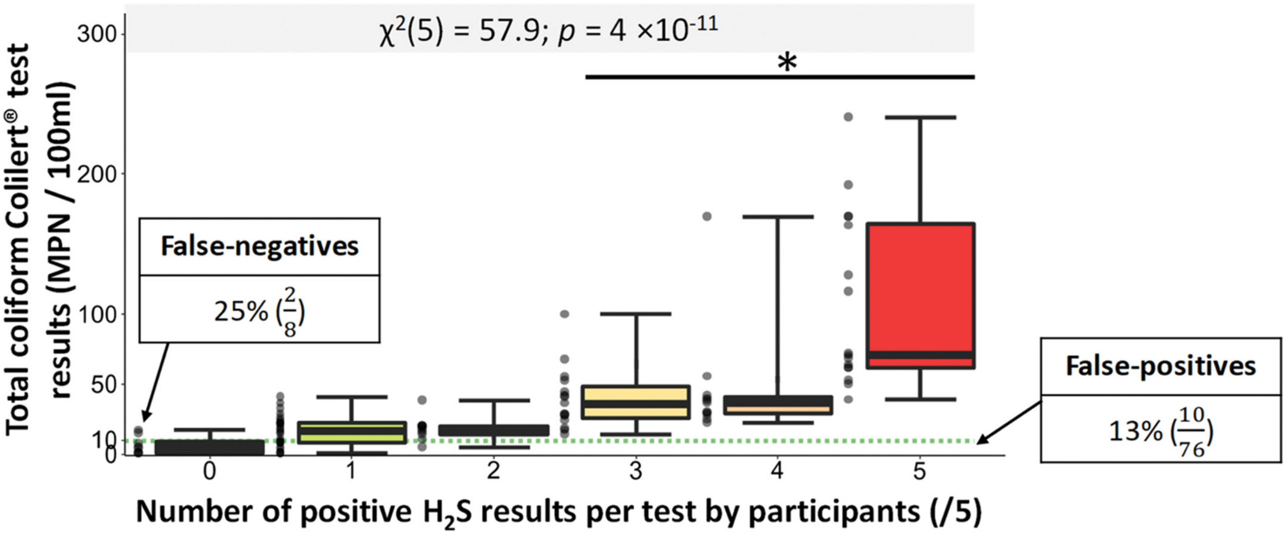


**Figure 6:** Comparison between the Colilert® test results obtained in the researchers' laboratory and the number of positive $H_2S$ responses generated by citizen scientists for a given water sample. Both rainwater and borehole water source samples are included here. Green dashed line shows the boundary between samples that measure intermediate-risk Colilert® measurements ($<$ 10 MPN/100 mL) and higher-risk samples. **Annotations:** Inset text shows results from Kruskal–Wallis testing for significant differences between the medians of samples. * - samples showing significantly higher Colilert® (R) test response, compared to the samples producing zero positive $H_2S$ responses. Significantly different samples identified using Dunn's test, modified using the Benjamini–Hochberg procedure ($p \leq 0.05$).

for the citizen science testing of 97% and 37.5%, respectively, comparing very favourably to previous studies in which researchers compared both the $H_2S$ kit results and Colilert® systems under laboratory conditions.[22] This study shows an increased sensitivity compared to the previous study (from 71% to 97%), while the decrease in specificity (from 100% to 37.5%) may be assigned to the small sample size of the water samples that did not elicit an $H_2S$ response (only eight samples, of which six were true negatives and two false negative samples having Colilert® measurements close to the 10 MPN/100 mL threshold value), coupled to variability in sampling and incubation conditions between the citizen scientists and the researchers in the previous study. The use of a single test kit for sampling was reported to have 64% reliability by Nhokodi and his colleagues[19,22]; increasing the sample size to five kits per sample improved reliability to 99.4%[19, 22].

Overall, this finding underscores the potential of $H_2S$ water testing kits in detecting water quality issues, with Colilert® measurements serving as a robust validation mechanism. The overall testing method is very sensitive to the presence of bacterial contamination in the existing water sources, but test specificity will require further addressing: while those samples that produced no detectable $H_2S$ responses maintained low coliform estimates (Figure 6) compared to other samples, two of these eight measurements failed to identify a moderate risk of microbial contamination in their water samples. The findings contribute to community health awareness, emphasising the need for vigilance in addressing false negatives to ensure water safety and supporting a comprehensive approach to water quality monitoring.

Of the 29 participants, all 29 elected to evaluate their rainwater sources weekly, while 15 of them additionally measured borehole water quality weekly. Of the possible total of 792 tests, 767 test results were returned by the citizen scientists at the end of testing, corresponding to a 96.8% completion rate by the cohort. Figure 7 presented the distribution of $H_2S$ test kit responses over the 18-week period (Figure 7).

As measured by the $H_2S$ kits, water quality varied considerably from household to household and from week to week (Figure 7). This variation prevented any analysis of the water quality as factors of time or of residential area among the participants (data not shown). While the survey indicated that rainwater was extensively used and trusted by the citizen scientists (Figure 5) and was often consumed without treatment, the findings presented in Figure 7A indicate that extensive variation in the quality of the rainwater existed. While 22 of the 29 participants recorded $H_2S$ kit measurements of zero at some point of the testing period (indicating a lower risk of consuming the water without treatment); only two (participants 11 and 18) had consistently low $H_2S$ measurements (✔ annotations; Figure 7). Comparatively, all participants recorded $H_2S$ kit responses of three and above, indicating significant microbial contamination of the water, at some point during the study (Figure 6); three of the participants (participants 4, 15 and 26) measured consistently high risks of drinking their rainwater untreated (× and × annotations; Figure 7A).

Borehole water (Figure 7B) had more consistent water quality compared to rainwater but showed elevated levels of risk overall. The aggregate distributions of the $H_2S$ test responses (box plots in Figure 7) showed that rainwater generated a median response of two positive $H_2S$ tests per sample, while borehole samples overall had three, representing a significantly higher aggregate response ($W = 47075$; $p$-value = $4\times10^{-12}$). Similarly, four of the participants measuring their borehole water reported consistent risks to drinking it untreated (× and × annotations; Figure 7B).

Among both water sources, ‘orange’ (1–4 positive kits) were reported in 67% of instances during the course of the sampling by the citizen scientists, while ‘red’ (five positive kits) were 14% of all tests, making a total of 81% of the water samples carrying some risk of microbial contamination when consumed without treatment.

In weeks in which five positive kits were reported, researchers and affected participants discussed strategies for treating the water source, including clearing out the water tank, cleaning gutters or boiling water before consumption. In informal conversations during the weekly sampling and reporting, community members would express that they were amenable to treating their water using these strategies; however,

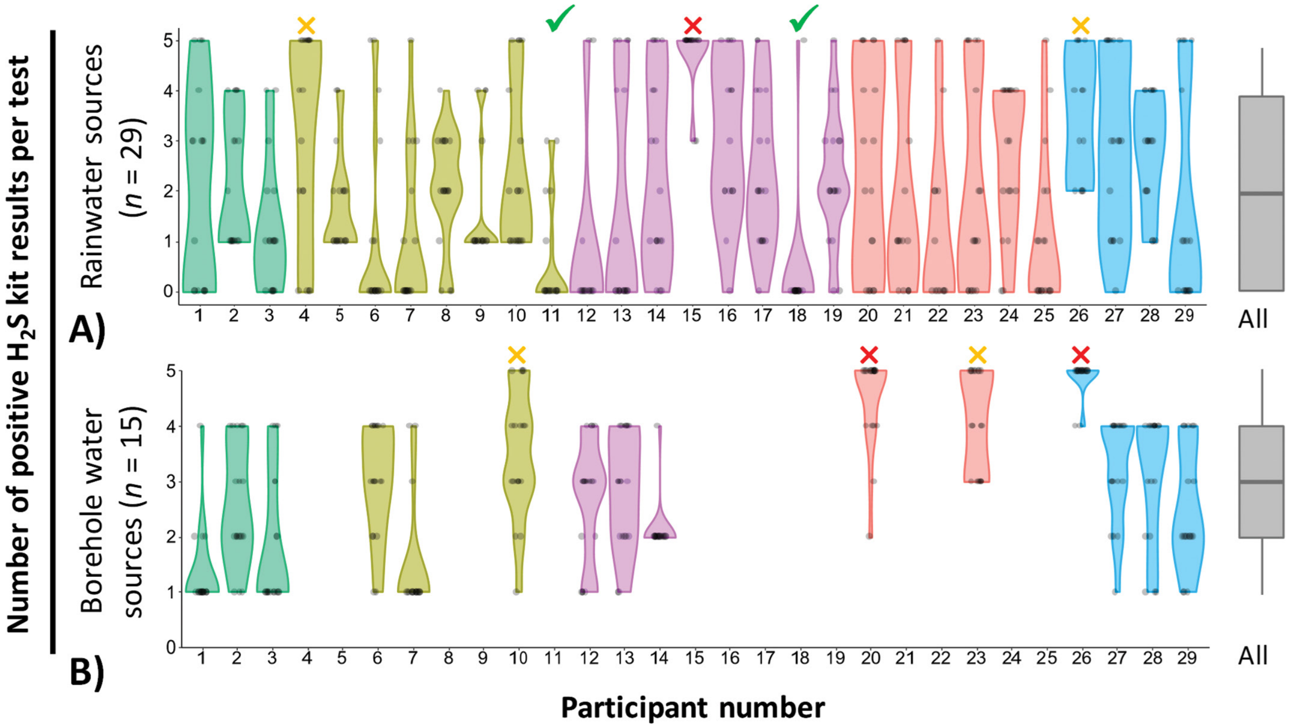


**Figure 7:** A comparison between the $H_2S$ results of the rainwater and borehole water, as monitored by the citizen scientists at Amakhala. (A) Rainwater sources ($n = 29$). (B) Borehole water samples ($n = 15$). Combined violin and dotplots show the distribution of individual responses, while the box plots at the end show the distribution of the combined $H_2S$ kit results for the two water sources. Violin plot colours indicate the residential area of participants, as depicted in Figure 3. **Annotations:** ✔ generally safe water: over 75% of measurements produced $H_2S$ kit responses of zero; × generally unsafe water: over 75% of measurements produce $H_2S$ kit response of 5; × generally unsafe water: a one-sample Wilcoxon rank test against the hypothesis that the samples are drawn from a population with a median measurement lower than 4, $p < 0.025$.

they were discouraged by the cost implications. Subsequently, some of the citizen scientists discussed boiling the water using outdoor fires and storing it for use over a longer period, decreasing electricity costs. Additional solutions included seeking financial assistance or subsidies from various stakeholders and exploring community-led initiatives to pool resources for water treatment. By acknowledging and discussing these cost implications, researchers and community members discussed potential solutions, including finding low-cost alternative treatment methods. These discussions and problem-solving sessions provided a platform for the community of Amakhala to strategise and find feasible ways to overcome cost barriers, supporting them to solve problems through changes in practices.

## Discussion

Through active participation, interpretation of the $H_2S$ kit results, and discussion of test-informed water treatment strategies, the citizen scientists communicated their ability to make informed decisions and take action to ensure water safety. Being a community focused activity, participants shared and discussed findings among themselves, frequently consulting one another when they were unsure of processes. The high completion rate further signifies continued agency and interest in engaging in the monitoring process.[35-39]

During training workshops, communication channels were established, and the researchers could provide instructions, guidance and answer questions. This initial interaction set the foundation for ongoing communication throughout the project.[40,41] Weekly data collection and feedback sessions at each of the villages maintained these channels, providing an avenue for participants to report results and discuss challenges during the water quality monitoring. These sessions enabled citizen scientists to analyse the water quality results together with the researchers and have further conversations around monitoring practices and mitigation strategies.[40,41] This feedback loop may have contributed to the completion rate of 96.8% by the cohort during the 18-week testing period (Figure 7), and through a culture of open communication and helped to ensure the accuracy and reliability of the collected data. This collaborative nature of the programme, applying RRI and engaged research principles in agenda setting in the approach, may have fostered a sense of shared ownership and active involvement in the scientific process.

## Conclusions

Insights into the complexity of this form of community-based water quality monitoring have highlighted the need for a rapid water quality test that can enable communities to test their water and receive results within hours. A limitation of this approach, identified by both communities and researchers, is the validity of the test results given the three-day incubation period required to obtain results. Communities are also reliant on access to the water testing kits provided by researchers. Reflecting on this research, and with knowledge of the specific contextual requirements and available resources, a novel testing technology was identified that is currently under development by the researchers, and which aims to provide more rapid results in a sustainable way. Community participants expressed interest in participating further in the evolution of this new technology, validating the use of a citizen approach in RRI and highlighting how the iterative nature of engaged research ensures community engagement from the outset and throughout the project cycle.

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## Data availability

The data supporting the results of this study are available upon request to the corresponding author.

## Declarations

We have no competing interests to declare. We have no AI or LLM use to declare. This study was approved by the Rhodes University Human Ethics Committee (RU-HEC), with the approval number 2021-1415-5941.

## Authors' contributions

T.N.: Conceptualisation; methodology; data collection; sample analysis; data analysis; validation; writing – the initial draft; writing – revisions; funding acquisition. R.F.: Conceptualisation; data analysis; validation; writing – revisions; student supervision. J.C.B.: Conceptualisation; methodology; data analysis; writing – revisions. J.L.: Conceptualisation; methodology; writing – revisions; student supervision; project leadership; funding acquisition. All authors read and approved the final manuscript.

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