

Development and operationalization of a citizen science framework for hydrological monitoring and knowledge co-generation

Alemseged Tamiru Haile^{a,*}, Tilaye Worku Bekele^b, Mintamer Ferede^b,
Kirubel Demissie^a, Hailay Zeray Tedla^c, Yirgalem Teshale^d, Gudina Legesse Feyisa^e,
Amare Hailelassie^a

^a International Water Management Institute (IWMI), P. O. Box, 5689, Addis Ababa, Ethiopia

^b Water Technology Institute, Arba Minch University, P.O. Box 21, Arba Minch, Ethiopia

^c Water and Environmental Engineering, Department of Built Environment, Aalto University, Espoo, Finland

^d South Sodo District, East Gurage Zone, Central Ethiopia Region, Ethiopia

^e College of Natural and Computational Sciences, Centre for Environmental Science, Addis Ababa University, Ethiopia

ARTICLE INFO

Keywords:

Citizen science
Citizen science framework
Knowledge co-generation
Nature-based solutions

ABSTRACT

Citizen science (CS) empowers communities in data collection and problem-solving, enhancing research inclusivity and local relevance. However, the absence of a comprehensive framework limits their development and potential contributions to sustainable practices. In this study, we developed and tested a CS framework for hydrological data collection and the co-creation of nature-based solutions (NbS). The framework has 3 major stages: establishment, operation and knowledge generation - each involving multiple activities. It was piloted in the Kelekindo watershed of Central Rift Valley Lakes Basin of Ethiopia, engaging the citizen scientists (CSts) in monitoring of rainfall, river water level, shallow groundwater (SGW) and water quality. The CS data allowed to investigate poorly understood hydrological behaviour of the watershed, including the *fill-and-spill* effect and characterization of an extreme runoff event. Co-interpretation of the data showed that SGW recharge could support thousands of farmers in practicing backyard irrigation. The river and well water in the study area were within safe limits for irrigation in terms of the commonly monitored water quality parameters. CSts were engaged in the selection and co-design of a priority NbS for watersheds. The study showed that a well-designed citizen science framework can generate reliable hydrological data and meaningfully engage communities.

1. Introduction

Citizen science (CS) has emerged as a powerful tool for enabling community participation in environmental monitoring, decision-making, and policy formation (Buytaert et al., 2014; Haklay, 2015). It is an emerging non-traditional data source for monitoring most indicators of the Sustainable Development Goals (SDGs), raising awareness, and mobilizing actions to achieve the SDGs (Fraisl et al., 2023). CS can also be effectively integrated into all phases of a community-based flood early warning system (Nigussie et al., 2025)

* Corresponding author.

E-mail addresses: A.T.Haile@cgiar.org, alemsegedtamiru@yahoo.com (A.T. Haile).

<https://doi.org/10.1016/j.hydrch.2026.100040>

Received 11 October 2025; Received in revised form 14 July 2026; Accepted 2 August 2026

Available online 9 August 2026

1998-9563/© 2026 The Authors. Published by Elsevier Ltd on behalf of Italian Hydrological Society (IHS). This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

and can transform community engagement in nature-based solutions (Loghmani-Khouzani et al., 2024). Engaging citizen scientists in data collection strengthens adaptive management by generating continuous learning. Jordan et al. (2016) highlight that data gathered through citizen science can support collaborative learning environments, helping reduce uncertainty and improve system understanding. Their review showed that learning plays a critical role in making conservation efforts more effective. Similarly, Aceves-Bueno et al. (2015) emphasized that well-designed citizen science programs provide cost-effective, reliable information while building community ownership of natural resources. Together, these studies demonstrate that citizen science enhances adaptive management by improving data quality, fostering learning, and encouraging local stakeholders' stewardship.

The successful application of CS to such diverse purposes is highly dependent on the quality of the program's initial stages. However, activities in the initial stages, including the community engagement process, are inadequately documented in the CS literature, which usually prioritizes data accuracy (Walker et al., 2016; Tedla et al., 2022) or CS data use in modelling (Starkey et al., 2017).

Only a few studies have published frameworks for a CS program while offering limited details about the program's establishment. Azizi et al. (2023) presented a CS framework for characterization and modelling of urban pluvial flooding. Their framework involved three phases, with the first phase covering the initial engagement of citizen scientists. However, crucial activities of the initial engagement (such as criteria for selecting citizen scientists and their engagement in deciding the incentives and type of monitoring data) have not been well described. Tran et al. (2024) presented 5-steps for citizen science engagement that included preliminary site visits, recruiting citizen scientists, training citizen scientists, data collection and data quality control, and publishing. They did not engage citizen scientists in deciding which variables to monitor and citizen scientists' motivation and performance analysis have rarely been addressed. More widely in hydrological CS, Nardi et al. (2022) described a much broader and conceptual framework referred to as the CANDHY transdisciplinary framework, with a broader applicability across many natural and social sciences.

Studies of CS often describe only selected components of their program frameworks, providing limited detail on how the initiatives are designed and implemented. Nath and Kirsche (2023) found that most publications mention elements such as recruitment, training, data collection tools, and communication, but rarely present a complete, explicit framework. This partial reporting creates significant gaps in our understanding of how CS programs are structured and managed. Overall, this widespread lack of comprehensive documentation on the design and implementation of CS program establishment, encompassing recruitment criteria, training, community outreach, and participatory goal setting, hinders the program's inclusiveness and sustainability.

The effectiveness of CS programs hinges on strengthening and addressing critical gaps during their establishment stage. These gaps include (i) limited attention to the establishment of the CS program (Walker et al., 2016), (ii) use of citizens only as data collectors (Babiso et al., 2023), (iii) limited evidence of engaging citizens in data interpretation and knowledge co-generation (Nigussie et al., 2025), (iv) lack of opportunity for citizen scientists to guide the program establishment (Upriety et al., 2019), and (v) lack of outreach programs before recruiting citizen scientists that can hinder inclusivity of the program. Addressing these gaps is crucial for citizen science programs to have the desired impact. In this regard, the importance of seeking a point of entry for citizens' engagement in science by understanding community needs, capacity, and power interactions is emphasized by Upriety et al. (2019). However, the potential of CS in nature-based solutions (NbS) to safeguard the environment and benefit society remains untapped. Conrad and Hilchey (2010) advocated for more case studies to demonstrate the use of CS data by decision-makers and identify barriers and strategies to overcome them.

There are several constraints to an inclusive CS program. For instance, ownership of groundwater wells is often a criterion for the recruitment of citizen scientists for groundwater monitoring (Little et al., 2016). Rainfall monitoring may exclude citizens who do not have a large compound to minimize the interference of buildings and tall trees with measured rainfall (Tedla et al., 2022). Several women in rural areas of Ethiopia are unwilling to volunteer due to heavy work burden and illiteracy (Nigussie et al., 2018). They can be included in the CS program by engaging them in monitoring sites that are situated very close to their houses (e.g. rainfall and shallow groundwater wells in their backyards). Another challenge is how to ensure that most community members have information about the CS program before its establishment. Outreach programs can be helpful in this regard. This can be by advertisement of the CS program through websites (Fehri et al., 2020) or in newspapers (Little et al., 2016) to reach a wide range of potential volunteers.

In the recent decade, we witnessed the emergence of CS programs in Ethiopia. A CS program was piloted for shallow groundwater (SGW) governance in Dangila district of Lake Tana basin, where volunteer engagement led to the generation of time series rainfall, SGW level and river discharge data. The data were used to study rainfall-runoff relationships and estimate available recharge to support backyard irrigation in the district and adaptive management (Gowing et al., 2020). In the Rift Valley Lakes Basin, Ferede et al. (2020) applied CS for SGW recharge estimation in a small upland watershed, whereas Babiso et al. (2023) demonstrated that citizen scientists were able to generate river water quality data as good as professionals for Meki River. Published studies in Ethiopia mostly target providing evidence on the quality of citizen data (Walker et al., 2016; Tedla et al., 2022), while studies demonstrating the value of CS data are emerging (Tedla et al., 2024; Nigussie et al., 2025). Ministry of Agriculture and Ministry of Water and Energy recognized the importance of such programs by initiating efforts to include them in the evaluation of the hydrological benefits of sustainable land management programs and basin hydrological monitoring plans, respectively (Personal communication in June 2025). Despite these demands for CS programs, there remains a lack of a framework to guide the establishment and operation of such programs. The only available guidelines target training citizen scientists to monitor hydrological variables in Ethiopia (Walker et al., 2019).

Existing citizen science literature reveals three major shortcomings that motivated us to initiate this study. First, most studies are largely data-oriented, focusing on data collection, program promotion, or improving data trustworthiness rather than presenting a holistic program design (Nath and Kirsche, 2023). Second, they report only isolated components of CS frameworks, with comprehensive, well-documented frameworks remaining scarce. Third, available frameworks offer limited guidance on linking CS initiatives

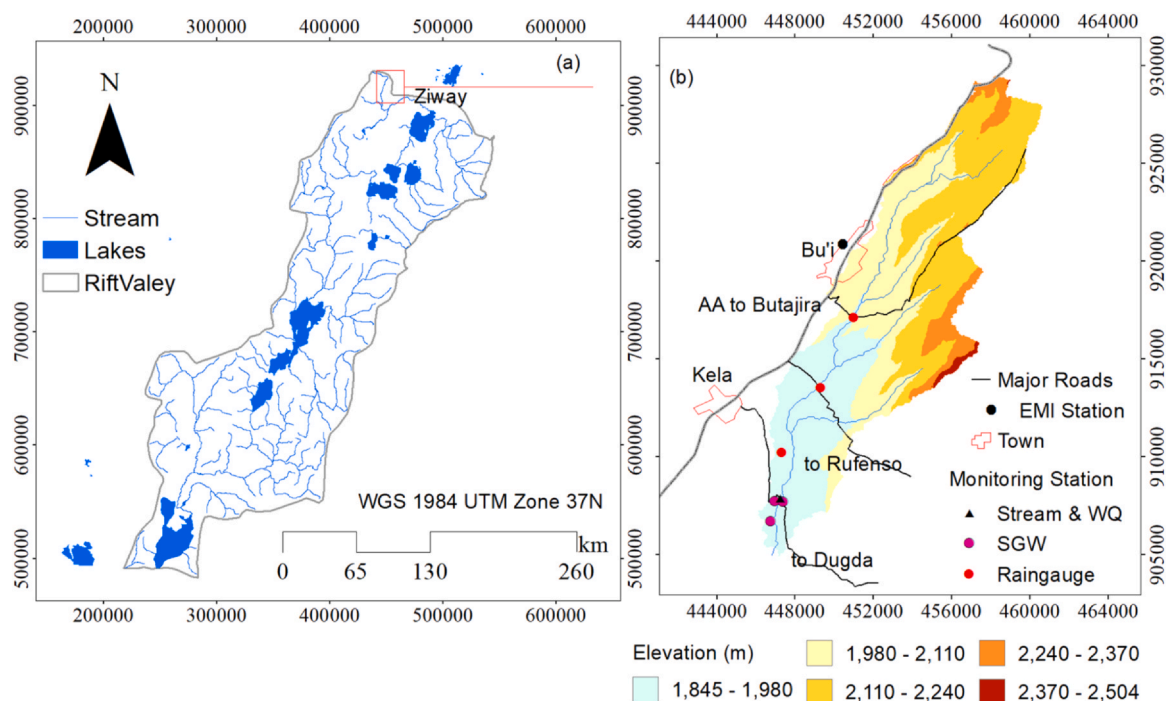


Fig. 1. The location of Kelekindo watershed in the Rift Valley Lakes basin and its elevation variation along with the citizen science monitoring sites.

with development projects or adapting them to regional contexts. This highlights the need for context-specific, fully documented frameworks that demonstrate how CS can effectively inform water resources management.

The main objective of this study is to develop, apply and document a systematic approach for the establishment and operationalization of a CS program through meaningful engagement of stakeholders, including the community, and leveraging lessons drawn from past and ongoing CS programs. With an aim to fill data and knowledge gaps in the planning and implementation of nature-based solutions, including soil and water conservation interventions, a CS program was set up at Kelekindo watershed, which is situated in the Central Rift Valley Lakes Basin of Ethiopia. The framework presented in this study will guide the appropriate set-up of CS programs not only for data collection but also knowledge co-generation to benefit the application of nature-based solutions, in terms of adaptive management, in watershed management.

2. Methods

2.1. Study sites

The study site is the Kelekindo watershed, which is situated in the Rift Valley Lakes Basin. It is a small upland watershed of the Meki catchment that feeds Lake Ziway. The terrain elevation of Kelekindo varies from 1845 to 2054 m a.m.s.l (Fig. 1). Kelekindo is selected for this study because it is one of the intervention sites for the Nature-Based Solution for Sustainable and Inclusive Development (NSSID) project, and the case study site of the research component of the project. The NSSID project supports landscape restoration through nature-based solutions. It promotes sustainable forest management, biodiversity conservation, and improved livelihoods for communities, small farmers, entrepreneurs, and small and medium enterprises. The initiative tackles soil acidity, land degradation, and watershed challenges while strengthening agricultural value chains. Through measures such as moisture conservation, water harvesting, and strategic runoff capture, NSSID enhances water availability where and when it is most needed.

Table 1 shows the characteristics of Kelekindo watershed in terms of location, size, climate, and land cover. The watershed experiences significant year-to-year variability in annual rainfall, with the lowest total being only about one-third of the highest. Annual rainfall exceeds potential evapotranspiration by only 109 mm. Agricultural land dominates the watershed, followed by grazing areas, shrublands, bare land, and settlements.

2.2. Methods for the establishment of citizen science programs

In this study, the CS framework and program were intentionally presented together because the framework evolved directly from our ongoing citizen science activities. At the start of implementation, the framework was not yet finalized; instead, it was developed iteratively by documenting our own field experiences and incorporating feedback from citizen scientists and project partners. For this reason, it was important to describe the CS program alongside the framework.

Table 1
Key features of the Kelekindo watershed.

Watershed name	Kelekindo
Longitude	38.51
Latitude	8.18
Watershed size (km ²)	125
Mean annual rainfall (mm)	998.0
Range of annual rainfall (mm)	561.4–1517.3
Mean temperature (°C)	17.8
Mean annual PET (mm)	888.9
Annual rainfall – PET (mm)	109.1
Dominant land cover	Rain-fed crop land

We developed and applied a three-stage approach for CS programs in a small watershed in Ethiopia, aiming to enhance watershed management. The first stage is referred to as the early/initial stage (establishment) of a citizen science program. The second stage is the operational stage, with daily to bi-weekly engagement of citizen scientists. The third stage is knowledge co-generation, where citizen scientists, district-level experts, and researchers meet at quarter to annual time intervals to generate knowledge. Fig. 2 shows an infographic summary of these three stages and the corresponding activities of our CS program.

2.2.1. Early (establishment) stage of the CS program

2.2.1.1. Clear planning and objectives of the CS program. During the planning stage of the CS program, the main aim was to align the program with an existing NbS initiative. This alignment is believed to help define a clear purpose, demonstrate value, and ensure sustainability over multiple years. In this study, the CS program was designed as part of the NSSID project. After a series of in-person and online meetings, the project coordinators reached a shared understanding about the importance of the CS program. They evaluated the ongoing NSSID project intervention sites based on factors such as the types and stages of planned watershed



Fig. 2. Framework for set-up and operationalizations of a citizen science program.

interventions, site accessibility for frequent supervision, and availability of multiple water users of the river and shallow groundwater. Based on this assessment, Kelekindo and Chemeri watersheds were selected as sites for the CS program. In this study, we targeted the Kelekindo watershed.

2.2.1.2. Initial assessment of the watershed. Our team travelled to the Kelekindo watershed for in-person meetings with district officials and to conduct a reconnaissance visit. We introduced the concept of CS to the head of the woreda agricultural bureau and discussed the benefits of the program to watershed management, sharing lessons learned from other watersheds in Ethiopia. Woreda is an administrative division (district) in Ethiopia. The key lessons from CS programs in other parts of Ethiopia included (i) sustaining citizen science programs relies heavily on strong support from the woreda administration and clear linkages with ongoing development initiatives, (ii) effective co-design and co-implementation are essential for ensuring community ownership and long-term relevance, and (iii) citizen science data generated from earlier initiatives played an important role in quantifying available water resources and informing local decision-making. Engagement of a para-hydrologist (an intermediary between the citizen scientists and researchers or experts) and the selection criteria for this role were also discussed. Based on past experiences of the International Water Management Institute (IWMI) (Haile et al., 2025), the main criteria for selecting a para-hydrologist included fluency in the local language, knowledge of the watershed, experience working with the community, computer literacy, and willingness to volunteer. Additionally, the para-hydrologist's work and life commitments should not require travel outside the watershed for extended periods. Using these criteria, the head of the agricultural office identified one para-hydrologist for the watershed.

Next, a meeting was organized with the para-hydrologist to explain the concept of CS and clarify responsibilities of a para-hydrologist. These responsibilities include coordinating monitoring activities, providing guidance and feedback to citizen scientists, collating and digitizing data, conducting basic data quality checks, archiving and sharing data with the project team, liaising with local stakeholders, and disseminating findings to the local community and district agricultural office. The para-hydrologist then organized a transect walk with our team, covering potential sites for monitoring, existing watershed interventions, SGW wells, and irrigation sites.

2.2.1.3. Co-designing the CS program with the community. Engaging the community in designing a CS program is crucial for fostering a sense of ownership and ensuring the program's success. In this study, a half-day meeting was conducted with selected members of the community identified by the para-hydrologist based on a set of criteria including location of their houses (upper, middle and downstream), social inclusion (gender and youth representation), and engagement in irrigation using SGW and river diversion. In Kelekindo, 15 community members (8 men, 7 women) attended the meeting, representing the upper (4), middle (4) and downstream (7) parts of the watershed. Participants included farmers, SGW well owners, and students, ensuring good representation of both men and women.

The purpose of the meeting with the community members was to reach a common understanding on the purpose of the CS program, demonstrate the monitoring equipment, identify the hydrological variables of interest for monitoring in each watershed, recruit citizen scientists, and identify candidate sites for the monitoring. The community members identified a range of NbS already being implemented in the watershed through community engagement by project partners and others. These include tree planting, gully rehabilitation, pond construction, and establishing area enclosures aimed at reducing soil erosion and protecting local ecosystems. The CS program is expected to generate data that will help expand these interventions to other parts of the watershed and assess their hydrological impacts using a hydrological model.

The para-hydrologist at each site facilitated the meeting starting with describing CS, emphasizing how the success of the program depends on the commitment of volunteers. The following criteria were discussed to identify the citizen scientists: respected by the community, literate enough to read and write data, spend most of their time within the watershed, and live near potential monitoring sites. Volunteers with the following attributes were prioritized: owners of wells to monitor SGW level, individuals with a large compound to host a rain gauge and become rainfall observers, and students were encouraged to monitor water quality. Community members discussed each criterion and suggested potential citizen scientist (CSts). In the Kelekindo, 9 CSts were identified (3 for rainfall, 3 for SGW, 2 for water quality and 1 for stream water level monitoring).

Similarly, technical requirements for selecting the monitoring site of each hydrological variable were presented to the community members and they suggested potential sites based on the requirements. For the monitoring network design, we considered several key factors, including watershed size, the placement of NbS, the location of irrigation sites, and the availability of citizen scientists to support hydrological data collection. While a rain gauge operated by the Ethiopian Meteorological Institute (EMI) covers the up-stream area, the middle and downstream sections lacked formal monitoring infrastructure. To address this gap, we installed additional rain gauges through our citizen science program, ensuring comprehensive spatial coverage across the watershed.

Table 2 shows the monitoring equipment, variable, number of stations, and monitoring frequency at Kelekindo watershed. Citizen scientists, para-hydrologist, and local community members participated in the monitoring set-up, which consisted of equipping citizen scientists with monitoring equipment and data recording sheets.

2.2.1.4. Set-up of monitoring sites. Plastic rain gauges, manufactured by EMI, were used for rainfall monitoring (Tedla et al. 2022). A low-cost rain gauge in the form of a graduated plastic cylinder was used in this study. The catch area of the rain gauge is 400 cm². It has a 150-mm capacity with 0.25 mm increments in the graduated marks, but the increments increase with the rainfall depth. The rain gauges have been installed in the backyard of the citizen scientists who volunteered to monitor rainfall. Sites free from the interference of cattle, houses and tall trees were identified to install the rain gauges. A dip meter was provided to each of the volunteers who monitor SGW depth below a reference level. A visible and stable part of the well cover was identified as the reference

Table 2
Monitoring equipment, variables, number of stations and monitoring frequency in Kelekindo.

Equipment	Variable	No. of stations	Monitoring frequency
Plastic rain gauge	Rainfall amount	3	Daily at 9:00 AM
Dip meter	Shallow groundwater level	3	Daily, 6:00 AM
Rope, measuring tape and spirit level	River water level	One	Daily, 6 AM
LaMotte test strips	Water quality parameters (Nitrate, Nitrite, pH, Alkalinity, Total Hardness, Ammonia, and Phosphate)	One site for the river One site for SGW	Start and middle of each month
Plastic bottles to grab water samples	Sediment concentration	One river station	During runoff events

to measure water depth, and it was marked with a painting. The well cover was first cleaned to make sure that it was free of dust. A brush was used for the painting. We allowed the paint to dry before handling the well cover.

An existing bridge site was identified to measure river water level at Kelekindo watershed. The river gauging site meets the key technical requirements, including a straight channel reach, no backwater effects, and flow confined within the banks across all flow conditions. It is also free from aquatic vegetation and remains accessible during both dry and wet seasons. The only noted limitations are minor erosion and sediment deposition observed at the Kelekindo location. This problem was addressed by measuring river cross-section before and after a rainy season. LaMotte test strips (LaMotte, Warwick, UK) were provided to the citizen scientists who monitored river and SGW qualities. The test strips measure seven water quality parameters which are Nitrate (mg/L), Nitrite (mg/L), Ammonia (mg/L), Phosphate (mg/L), pH, total Alkalinity (mg/L) and Total Hardness (NTU).

2.2.1.5. Training of para-hydrologists and citizen scientists. We organized hands-on training to the CSTs during the set-up of the CS program. They were introduced to the monitoring equipment (Table 2), data recording sheet and the monitoring time and frequency. They practiced monitoring for a day and then received feedback on the following day. Strategies to minimize repeating common mistakes in monitoring and recording of data were discussed based on lessons from other CS programs (Tedla et al., 2022; Mengistie et al., 2024). Some common mistakes include transcription (misreading or mistyping of data) and transposition errors (digits were accidentally reversed when assessed by three or more peers). Therefore, the citizen scientists agreed to allocate adequate time for reading and recording the data as well as to check the position of the decimal point repeatedly, before leaving the gauging site. The para-hydrologist attended the citizen scientists' training. Then, they practiced provision of feedback to the citizen scientists based on inspection of the data recording sheets.

2.2.2. Operational stage of the CS program

The operational stage consisted of monitoring, data transfer and supervision, data pre-processing and quality assessment, and providing feedback to the citizen scientists. Rainfall was monitored daily at 9:00 AM, consistent with the practice at EMI. River water levels were monitored every day at 6:00 PM, aligning with the schedule used by the Ministry of Water and Energy (MoWE). Shallow groundwater levels were monitored daily at 6:00 AM, before water was fetched, to avoid disturbance of the static water level.

Water quality parameters were measured bi-weekly for both the river and SGW. For measurement of nitrate, nitrite, pH, Alkalinity, and Total Hardness, the test strip was immersed and swirled two times in the water sample, and it was removed with pad face up. Total hardness and total Alkalinity were measured immediately while pH, Nitrate and Nitrite were measured 30 s after the test strip was removed from the water sample. Ammonia was measured by immersing the test strip for 5 s and then comparing the test strip color with the printed color chart on the test strip box. For phosphate measurement, the test strip is bent and placed in the cap of a test tube containing 10 ml of water. The phosphate concentration is determined after gently inverting the tube five times and comparing the color of the water sample to the provided chart. Refer to Babiso et al. (2023) for accuracy of the water quality data measured by the test strips in Ethiopia. The citizen scientists' data, expressed as percent of synthetic standard solution concentrations, indicated good agreement for selected water quality parameters: $123.8 \pm 24.7\%$ for PO_4^{3-} , $115.6 \pm 6.3\%$ for NO_3^- , $105.8 \pm 7.4\%$ for pH, and $133.3 \pm 23.6\%$ for NH_4^+ . The authors also reported no statistically significant differences between values of most parameters recorded by citizen scientists and experts.

Data recording sheets were collected by the para-hydrologist at the end of each monitoring month. The para-hydrologist conducted a basic data quality check (Tedla et al., 2022) of the recorded data and informed CSTs about any data recording errors so that they would not be repeated. The para-hydrologists conducted a meeting with each citizen scientist every two weeks. During the meeting, they discussed the data recording errors and identified their sources. This was followed by a discussion on how not to repeat the errors in the future. Citizen scientists also discussed any problems faced during the visit of the para-hydrologist to seek a solution.

The para-hydrologists entered the collected data into a computer and shared it with IWMI researchers, who undertook visual and statistical analysis (correlation) of the data to identify any suspicious data. The results of the data quality check were communicated to the para-hydrologist, who regularly provided feedback to the citizen scientists.

2.2.3. Knowledge co-generation

Knowledge co-generation in this study consisted of data analysis and interpretation with citizen scientists, annual workshops for adaptive planning, identification and co-design of an appropriate NbS. This also involved refresher trainings for citizen scientists and para-hydrologists. These activities are described below.

2.2.3.1. Data analysis and interpretation. River water level data collected by citizen scientists were converted to river discharge values using Manning's equation (Alves et al., 2017). We engaged the para-hydrologist to measure key parameters - such as the longitudinal slope of the river, riverbank and bed materials, and cross-sectional area - which served as inputs for discharge estimation. The measurements were taken using equipment that can be easily accessed in rural areas, including a tape meter, plumb bob, spirit level, rope and sticks. For the longitudinal slope of the river, the rope was stretched between two sticks separated by a 10 m distance along the river channel. The rope was placed on the ground at the upstream stick, and then the spirit level was used to ensure horizontal alignment of the rope along the river. This was followed by the measurement of the height difference between the rope's position on the stick and the ground surface at the downstream stick. A tape meter was used to measure the height difference. Finally, the ratio of the height difference and the horizontal distance between the sticks was used to estimate the longitudinal slope of the river. For measuring the river cross-section, the rope was placed across the river between two sticks placed on the riverbanks. It was placed on the ground on the bank with the lowest elevation, and horizontal alignment was ensured with the spirit level. The vertical distance between the horizontal rope and the water level or riverbed was measured at 2-meter intervals with a plumb bob and measuring tape. Pictures of the riverbank and bed materials were taken and compared against references to determine Manning's roughness coefficient.

The Thiessen polygon method was used to convert daily rainfall amounts recorded by three citizen scientists into watershed average rainfall amounts. A joint plot of watershed-averaged rainfall and river discharge was then used to graphically evaluate the watershed response to rainfall.

Shallow groundwater level data collected during the rainy season by citizen scientists were analyzed using the water-level fluctuation (WLF) method, a widely used technique for estimating recharge (e.g. Ferede et al., 2020). For this study, groundwater recharge was estimated using the following equation (Ferede et al., 2020):

$$Re = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \quad (1)$$

where: S_y is specific yield (-), which was estimated based on soil texture, h is the depth to water table (m), t is time (day) and Δh is the cumulative rise (i.e. change) in groundwater level. Declining groundwater levels prior to a rainfall event were extrapolated to their expected positions had there been no precipitation. The rise (Δh) was then estimated as the difference between the peak level and the extrapolated antecedent recession level at the time of the peak (Healy and Cook 2002). We extrapolated the antecedent recession water level manually through graphical approach (Ferede et al., 2020). The water-level rises which occurred during dry periods were considered to occur because of observation error and were excluded from the recharge assessment.

Walker et al. (2019) analyzed the rainfall-recharge relationship for Ethiopia based on a review of forty-nine quantitative studies, and their relation was used to estimate recharge in Kelekindo watershed. The equation to estimate recharge (R) using annual rainfall amount (P) in mm reads as follows:

$$R = 136.6 - 0.3005P + 0.00271P^2 \quad (2)$$

Surface water and SGW quality were monitored as part of the citizen science program to assess suitability for various uses, including drinking and irrigation purposes. Each water quality measurement was compared against World Health Organization (WHO) and Food and Agriculture Organization (FAO) standards to evaluate its safety and suitability for drinking and irrigation, respectively.

2.2.3.2. Co-interpretation of citizen science data. Various meetings were held with the citizen scientists to discuss rainfall, streamflow, SGW and water quality variability and associated impacts. The data collected by the CSTs were used to guide the discussions. Observed magnitudes of rainfall at multiple sites were presented to them to discuss how the observed magnitudes and variabilities agree or disagree with their previous perception of rainfall variability in the watershed. Water variabilities in multiple wells were converted to recharge amounts to estimate potential land size that can be irrigated using wells. Further, water quality data was presented, and potential pollution sources were discussed. Discussions were also held with the CSTs to reach a common understanding about the implications of the river and SGW qualities for drinking and irrigation purposes.

2.2.3.3. Co-identify watershed management interventions. A session was dedicated to knowledge generation during the various meetings with the citizen scientists. First, they conducted participatory mapping, discussing the basemap of the study area for a better understanding of existing features on the map. Next, they added new features (water harvesting ponds, enclosure areas and irrigation sites) to the map. They have also indicated the names of the streams, their village, existing pond site, rain-gauge site, and other relevant features on the map.

During the community meeting, participants identified the priority intervention types that can lead to better watershed management while introducing short-term benefit to the community. They located existing water harvesting ponds on the basemap. These ponds were constructed by the NSSID project to supply water for domestic purposes and cattle that otherwise would have travelled long distance to the river. The citizen scientists also proposed minimum dimensions of the ponds but requested for support for detailed design.

Next, the CSTs in Kelekindo identified multiple criteria for pond site selection. These criteria are morphology, hydrology, conflict, risk and economic benefits (Table 3). Based on these criteria, the citizen scientists identified suitable pond locations on the basemap. The existing ponds in the watershed have a size in the order of 25 m x 25 m, but the citizen scientists advocated for larger pond size to serve the community throughout the year.

Table 3
Pond site selection criteria used by the citizen scientists.

Morphological and hydrological	Economic benefit	Risk	Conflict
Soil with low erodibility and poor infiltration rate. Uncultivated land, preferably grazing or bare land. Minimum pond size of 25 m x 25 m. Availability of adequate runoff to be diverted to the pond.	Ease of access (E.g. near settlements and irrigable land). Availability of land to engage the youth in nursery, beekeeping and cattle fattening.	The downstream of pond sites should be free from any economic activities (farmland, households, etc.) to reduce the impact of overflows during heavy rains.	Consider sites where there is minimum or no conflict for land or water use. Consider land administered by the local authority.

2.2.3.4. Adaptive planning. Quarterly and annual meetings were organized with CSTs. The purpose of the quarterly meetings was to provide regular feedback and refresher training to CSTs and the para-hydrologists to continuously improve their skills and knowledge. Further, the quarterly meetings were used to facilitate knowledge co-generation. On the other hand, the purpose of the annual meetings was to evaluate the performance of the citizen science program and plan for the next year based on lessons learned and challenges faced in the previous year.

In 2025, we organized a one-day annual workshop with citizen scientists, para-hydrologists, and woreda experts and officials. The format of the workshop included presentations about the citizen science program, data and knowledge generated by the CSTs. The framework for the establishment and operation of a CS program was also presented. In the workshop, four groups were formed to gather feedback that supports improvement of the CS program framework to benefit identification, design, implementation, and evaluation of nature-based solutions.

3. Results

3.1. Quality of the citizen science data

The quality of rainfall data collected by the CS program was evaluated by visually inspecting each record across the three stations. We did not find many suspicious records apart from couple of data entry mistakes by the para-hydrologist, who placed unnecessary spaces between numbers and misplaced decimal points for one of the records. Daily records at the three stations showed similar patterns with some exceptions. On 4 June 2024, the most downstream station recorded substantial daily rainfall amount (25 mm) while the two upstream stations reported no rainfall amount. During the refresher training, the citizen scientists (CSTs) remembered that the 4th of June 2024 rainfall covered only the downstream stations. We used this case to demonstrate the importance of writing remarks on the data recording sheet. The para-hydrologist was also informed to carefully undertake the data entry and assess accuracy of the data entry afterwards.

CSTs faced some challenges in consistently monitoring streamflow, especially when the river location was far from the observer's house, which demanded replacing the CSTs with a volunteer who lives very close to the river. Consequently, missing data was reported when the observer was engaged in various social or personal matters, including health-related problems. The CSTs also reported constant data value for few consecutive days in the dry season because the water was stagnant. We measured the river cross-section three times across the observation period to account for cross-section change in river discharge estimation because of erosion and sedimentation.

The common mistake for SGW monitoring was taking records after people fetched water from the wells which resulted in artificially lowered water level records. This happened a few times during the initial months of the citizen science program. During the refresher training, CSTs were again informed to take SWG level records at 6:00 AM before anyone starts to use the well. The SGW records also had missing data records because the para-hydrologist lost one-month SGW level record while CSTs missed some records because of personal problem.

3.2. Rainfall-Runoff relationship from CS data

Fig. 3 shows the joint plot of daily rainfall and instantaneous streamflow of the Kelekindo watershed as recorded by citizen scientists. For the study site, both the hydrological year and the calendar year start on 1 January. Since the first daily rainfall event in the calendar year (which occurred in May), the watershed storage filled for 5 weeks before spilling and streamflow responded to high rainfall in July-October. Hence, the rainfall amounts in May and June were used to fill surface and subsurface storages; therefore, these rains did not generate significant streamflow in the watershed. This effect is referred to as the *fill-and-spill* effect in literature (Staudinger et al., 2017). Due to this effect, Kelekindo watershed stored significant amount of rainfall (171.3 mm) before releasing it.

On 2 August 2024, 14.92 mm of rainfall was observed in the Kelekindo watershed. The streamflow generated by this rainfall event was recorded at a sub-hourly time step, which was divided into direct runoff and baseflow using a graphical method for a hydrograph separation. Fig. 4 shows the direct runoff that increased from $0 \text{ m}^3 \text{ s}^{-1}$ to a maximum of $38.6 \text{ m}^3 \text{ s}^{-1}$ within one hour and thirty

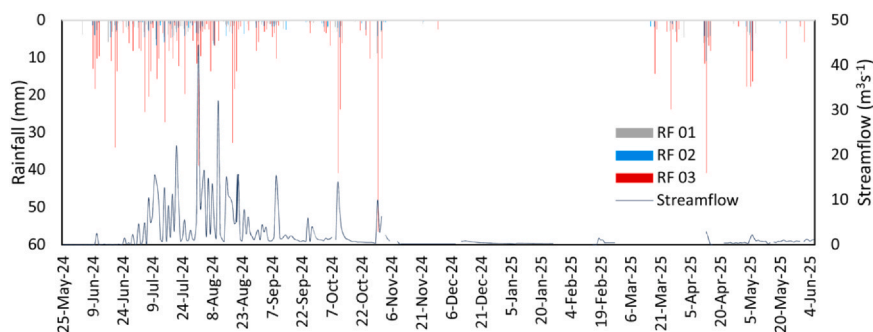


Fig. 3. Watershed averaged rainfall and instantaneous streamflow of Kelekindo River as recorded by citizen scientists.

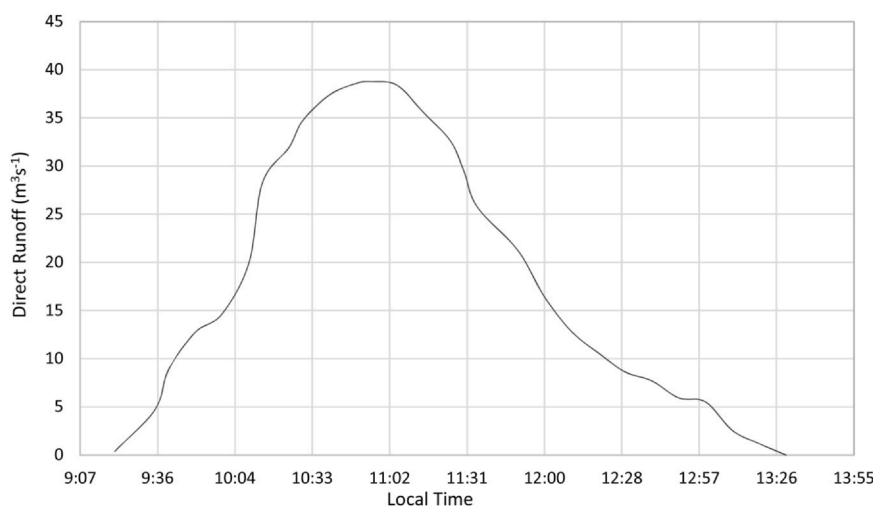


Fig. 4. Direct runoff of Kelekindo watershed as observed on 2 August 2024.

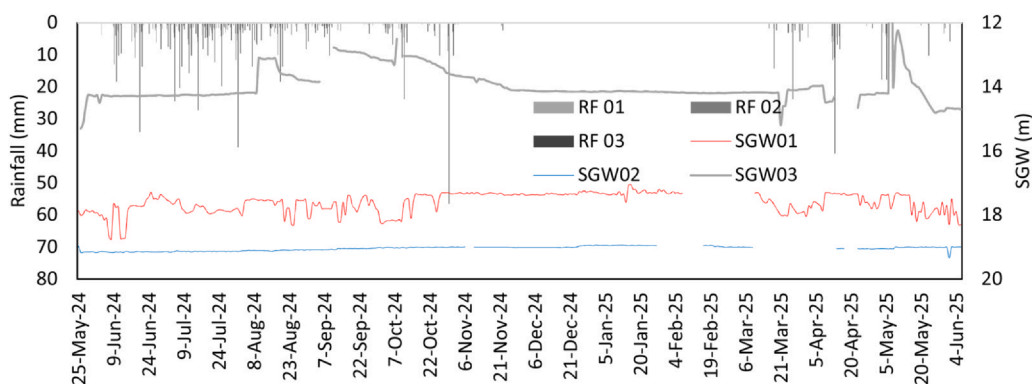


Fig. 5. Rainfall and shallow groundwater levels recorded by the citizen scientists from May to October 2024, Kelekindo watershed.

minutes, indicating the watershed generates rapid streamflow. The peak runoff did not show significant variation for nearly one hour, but it declined afterward, returning to the initial streamflow magnitude approximately six hours after runoff initiation. The recession limb extended over a longer period than the rising limb, suggesting interactions exists between surface and subsurface waters of the watershed, which requires further investigation.

3.3. Groundwater recharge of Kelekindo watershed

Fig. 5 shows a joint plot of rainfall and shallow groundwater data as recorded by the citizen scientists. Reference is made to Fig. 1 for the geographic location of the SGW wells. The SGW depths varied from 12.8 m to 19 m below the ground surface level (land

surface). SGW02 and SGW03 have the maximum and minimum depths during the observation period, respectively. SGW02 did not respond noticeably to the rainfall input because of its high depth among other factors that require further investigation. Although the water level of SGW03 is closer to the land surface than the other wells, this well did not respond to the rainfall input until 11 August 2025 (note: rainfall started on 8 June 2025). The response of this well was abrupt on 11 August which was attributed to surface runoff entering the well according to the citizen scientist who is monitoring the well. SGW01 has water depths higher than 17.4 m but it was highly responding to daily rainfall inputs, resulting in a highly fluctuating water level.

Citizen science data was used to estimate SGW recharge in Kelekindo watershed following the approaches presented in the methods section of this study. We found that the annual recharge of the Kelekindo watershed is 260 mm (26% of the total annual rainfall amount) when estimated using the water table fluctuation method. A recharge amount of 170 mm accounting for 10.7% of the total annual rainfall amount was estimated using the empirical method of Walker et al. (2019). Using a distributed rainfall-runoff model, Hulluka et al. (2024) estimated that most parts of Meki catchment including areas around Kelekindo have annual recharges greater than 200 mm per year. Hence, the citizen science data in this study provided results closer to what was reported by Hulluka et al. (2024) but deviated from Taye et al. (2022).

In this study, the potential irrigated area of the SGW was estimated using the minimum groundwater recharge from the empirical method (170 mm). The groundwater recharge depth was multiplied with the surface area of the woreda (28 km²) to convert it to the total volume of recharge (3.06×10^6 m³). We calculated the net crop water requirement by subtracting total rainfall from the crop's water requirement. The crop water requirement itself was determined using the Penman–Monteith reference evapotranspiration equation combined with appropriate crop coefficient. For a single irrigation season (October–May), the net crop water requirement of onion was estimated to be 541.12 mm indicating that 50% of the recharge could irrigate approximately 285 ha in the woreda. During one of the regular meetings, the CSTs noted that each farmer could irrigate ¼ ha of the backyard using SGW. Thus, 50% the annual recharge can support 1140 farmers in producing onions once per year.

3.4. River and shallow groundwater quality

3.4.1. Surface water quality of Kelekindo River

Citizen science data collected from the Kelekindo River suggests that surface water quality, based on most monitored parameters - nitrate, nitrite, alkalinity, total hardness, and phosphate - falls within the safe limits for irrigation as defined by FAO guidelines (Table 4). However, these assessments only consider chemical indicators and do not account for biological contaminants such as bacteria and viruses, which could still pose significant health risks. Ammonia concentrations exceeded safe limits (WHO: ≤ 1.5 mg/L) on 24-May, 8-June, 7-July, 23-July, 26-October, and 10-November. The ammonia contamination of rivers can be caused by human animal faeces and due to run off from agricultural runoff, livestock waste, and poor sanitation practices by humans.

In Table 5, the citizen science data indicate that the SGW quality in Kelekindo watershed is within safe limits for irrigation purposes for most parameters (Nitrate, Nitrite, Alkalinity, Total Hardness, and Phosphate) based on FAO criteria. However, these safe limits consider only the chemical parameters and do not account for biological contaminants such as bacteria and viruses, which could pose health risks. However, the pH of 6 in SGW during the wet season suggests slight acidity, which can be influenced by several factors, including rainwater getting into the wells, organic matter decomposition, and interaction of SGW with rocks and minerals. Ammonia concentration also approached or exceeded the safe limits for drinking in the wet season and for a few months after the rains stop.

Table 4

Surface water quality of the Kelekindo river as monitored by the citizen scientists. Note: green shows the water is safe for irrigation and drinking use, and red shows the water is not safe for use and yellow indicates need for caution in using the water.

Date	Nitrate	Nitrite	PH	Alkalinity	Total Hardness	Ammonia	Phosphate
24-May-24	0	0	7	40	120	3	0
8-Jun-24	0	0	7	40	120	3	0
22-Jun-24	0	0	NA	240	60	1	0
7-Jul-24	0	0.5	7	40	60	3	0
23-Jul-24	0	0	7	40	180	3	0
9-Aug-24	0	0	7.5	40	60	1	0
23-Aug-24	0	0	7	40	60	1	0
14-Sep-24	0	0	7.5	40	60	1	0
28-Sep-24	0	0	7	40	60	1	0
15-Oct-24	0	0	7.5	40	60	1	0
26-Oct-24	0	0	7	40	180	3	0
10-Nov-24	0	0.5	7	40	60	3	0
12-Jan-25	0	0	8	240	180	1	0

Table 5

Shallow groundwater quality (SGW01 well) of the Kelekindo watershed as monitored by the citizen scientists. Note: green shows the water is safe for irrigation and drinking use, and red shows the water is not safe for use and yellow indicates need for caution in using the water.

Date	Nitrate	Nitrite	PH	Alkalinity	Total Hardness	Ammonia	Phosphate
24-May-24	0	0	7.5	40	30	0.5	0
8-Jun-24	0	0	7	80	30	0.5	0
22-Jun-24	0	0	6.5	80	30	0.5	100
7-Jul-24	0	0	7.5	80	30	0.5	0
8-Jul-24	0	0	7.5	80	30	0.5	0
23-Jul-24	0	0.5	6	0	30	0.5	0
7-Aug-24	0	0	6	80	30	1	100
22-Aug-24	0	0	6	80	30	1	100
11-Sep-24	0	0	6	80	30	1	100
25-Sep-24	0	0	6	80	30	1	100
12-Oct-24	0	0	6	80	30	1	100
26-Sep-24	0	0	7	40	30	3	0
14-Oct-24	0	0	7	80	60	1	0
26-Oct-24	0	0	7	80	60	1	0
10-Nov-24	0	0	7.5	40	30	3	0
25-Nov-24	0	0	7	40	30	1	100
10-Dec-24	0	0	6.5	80	30	0.5	0

3.5. Knowledge co-generation with citizen scientists

Engaging CSTs in knowledge generation is often not well covered by many studies. In this study we engaged citizen scientists in knowledge generation by (i) co-interpreting the citizen science data and its implications, and (ii) identifying and co-designing a priority nature-based solution during regular meetings with them. In Kelekindo, the CSTs identified rainwater harvesting as the most beneficial NbS for the community. There is already experience of pond construction and use in the watershed. The CSTs stated that ponds will help to keep cattle away from rivers thereby reducing water pollution. They identified two potential sites for pond construction based on set of criteria defined by them. These criteria were presented in the methods section of this article.

A transect walk was conducted to georeference and assess the feasibility of the suggested pond sites. These sites were located on a government property with adequate overland flow and space for the pond construction. Previously constructed ponds were also visited, and lessons were drawn, including the need to provide proper silt traps and a spillway for excess water. Citizen scientists emphasized that the identified pond sites can create opportunities for the youth through engagement in beekeeping, cattle fattening, tree nursery, and growing vegetables.

The CSTs preferred the trapezoidal shape of ponds due to the aesthetic value and stability. They noted that the challenge of trapezoidal ponds is the restriction of movement during cleaning the bottom bed of the pond. They stated that pond size can be determined by the size of the available land with the minimum required dimensions of 25 m length on all sides. It was noted that ponds deeper than 5 m pose risks of cattle drowning, while shallow ponds can be immediately filled by sediments after two or three heavy surface overland flows.

4. Discussion

A one-day workshop brought together citizen scientists, para-hydrologists, and woreda experts to review the CS program, present data and the framework, and gather group feedback to strengthen its design, implementation, and evaluation for nature-based solutions. The details discussed by the workshop participants are presented in this section.

4.1. Benefits of the CS programs

The sustained engagement of CSTs for several months is because of multiple benefits offered by the CS program that align with established success factors (enhanced knowledge of data collection, awareness of the environment and motivation) for monitoring programs (San et al., 2020). CSTs demonstrated enhanced understanding of causal relationships between rainfall and hydrological variables, contributing to bidirectional knowledge transfer which is a critical component often missing in traditional citizen science

approaches. The program facilitated learning about community action consequences on soil erosion and water resource degradation, addressing the knowledge gap that Njue et al. (2019) highlight as a primary barrier to effective water resource management in data-scarce regions.

Through their meaningful engagement in the CS program, CSTs strengthened their understanding of rainfall variability and livestock-related river pollution, demonstrating locally relevant, actionable knowledge generation. The practical benefits extended beyond knowledge acquisition as CSTs monitoring groundwater levels received opportunities to purchase solar pumps through the NSSID program, exemplifying the tangible rewards that (Nath & Kirschke, 2023) identified as crucial for sustaining groundwater monitoring initiatives.

Student volunteers described their water quality monitoring as opportunities to apply classroom chemistry knowledge, reflecting the educational benefits documented by (Bonney et al., 2016) in their analysis of citizen science's role in expanding scientific literacy. The CSTs actively shared knowledge during formal and informal community meetings, creating the multiplier effect essential for scaling environmental monitoring impact.

The continued volunteer interest stems from enhanced community environmental awareness, access to scientific knowledge from researchers, and inclusion in watershed management decision-making—outcomes that mirror the empowerment benefits identified by (Fraisl et al., 2020) in their mapping of citizen science contributions to UN Sustainable Development Goals.

4.2. Overcoming challenges

The challenges identified by CSTs during the workshop reflect common obstacles documented in hydrological citizen science literature. Initial CSTs turnover, equipment maintenance issues, site accessibility limitations for para-hydrologist supervision, inadequate training for extreme events, and insufficient local administrative support are the main challenges identified in this study, which reflect common barriers (Weeser et al., 2018; Njue et al., 2019). Some volunteers stopped participating in our citizen science program because, after beginning the monitoring, they frequently travelled outside the watershed to visit family members. This disrupted their ability to continue the monitoring activities.

Our responsive approach included replacing faulty dip meters and rain gauge markings before the rainy season, and organizing meetings with local administration actions that align with the adaptive management strategies (Quinlivan et al., 2020). However, these reactive measures highlight the need for more robust quality assurance protocols for citizen science data credibility (Jollymore et al., 2017).

The identified need to increase para-hydrologist numbers reflects resource constraints common in low-income countries where conventional monitoring methods are expensive and logistically challenging (Njue et al., 2019). Frequent local administrator turnover demands persistent relationship building but manageable through sustained institutional support.

Critically, the extreme flooding events that overwhelmed CST capacity reveal limitations in our framework's preparedness for hydrological extremes. Citizen science programs often struggle with exceptional events that require specialized expertise, highlighting the need for hybrid approaches combining citizen and professional monitoring (Buytaert et al., 2014).

The co-interpretation process faced two main challenges: the varying educational levels of the citizen scientists and limited map literacy, as the approach had originally been tested in rural watersheds. To address these issues, we presented the citizen science data and maps in simplified, easy-to-understand formats to avoid overwhelming participants. We also structured the co-interpretation around a small number of focused tasks and conducted a series of meetings every few months. This experience highlighted the importance of adapting analytical materials to local capacities and allocating sufficient time for iterative engagement.

4.3. Opportunities to strengthen the citizen science program

The woreda experts and officials expressed interest in utilizing the data and knowledge generated by citizen scientists, if these are validated. To ensure that the citizen science data is accessible for current and ongoing projects, it was suggested to establish a strong collaboration between the natural resource team leader and the para-hydrologist to properly document the citizen science data in both hard copies and soft copies.

The citizen science program can be strengthened by involving the volunteers as beneficiaries of projects in the woreda. They can be beneficiaries of access to tree nursery sites, farm inputs, services of extension workers, and credit services. Further, the woreda has the capacity to mobilize the local community and materials for the implementation of the nature-based solutions identified and designed by the CSTs. The woreda experts suggested co-development of a proposal to attract funding for implementation of the selected interventions at a large scale. It was highlighted that the woreda needs to expand the CS program to other parts of the woreda.

The CS program was aligned with the NSSID project for sustainability and upscaling to other watersheds. Hence, NSSID and other related projects can address some of the challenges faced by the CS program. The project can organize training workshops for CSTs and the community to enhance the exchange of experience and knowledge, create awareness among local administration and other stakeholders to support the program, and strengthening the communication channel between all actors involved in the program.

The knowledge co-generation process tested in the Kelekindo watershed can be replicated in other NSSID watersheds, not only for NbS but also for the identification of a suitable crop type. NSSID and other related projects can use the CS program as an entry point to demonstrate the drawbacks of inorganic farming practices, including the use of artificial fertilizers and pesticides, and poor livestock waste management.

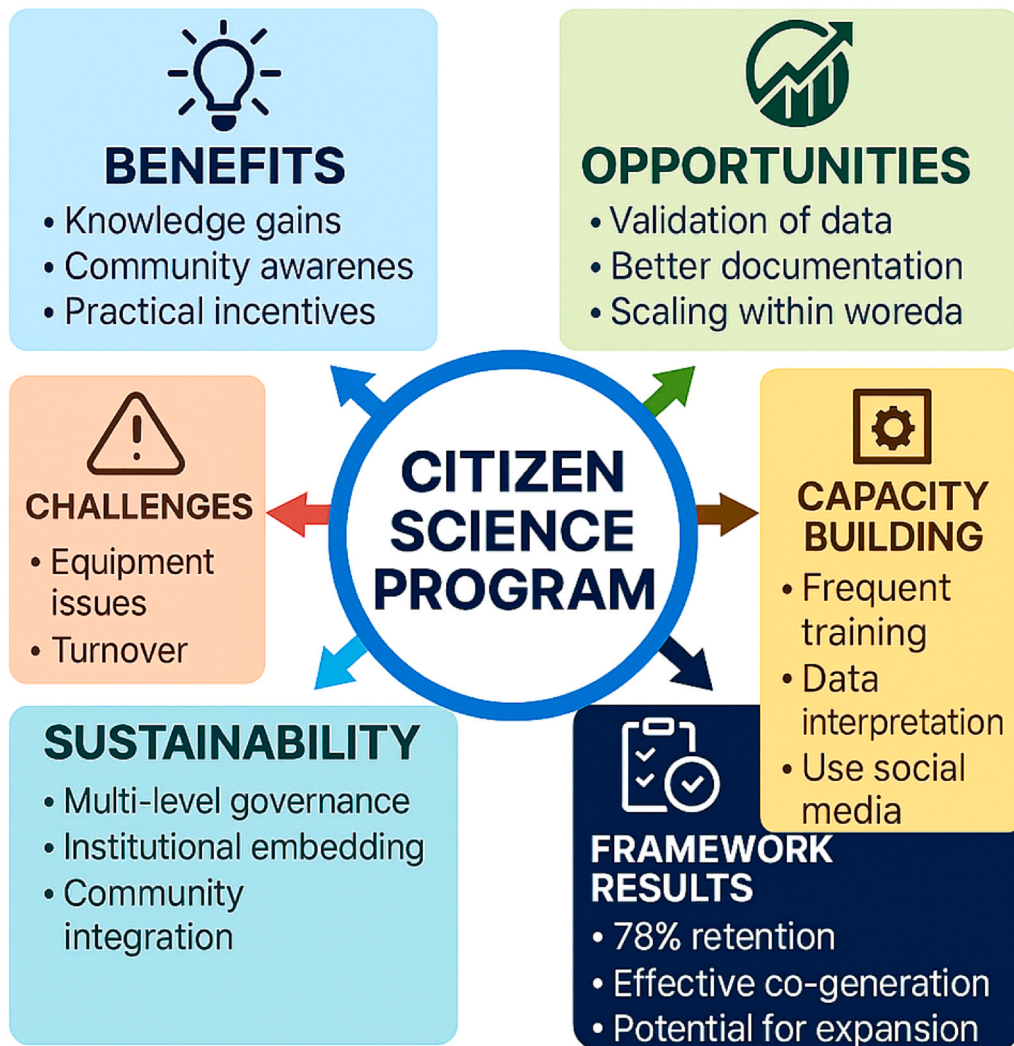


Fig. 6. Summary of the main outcomes of the discussion during the annual review workshop with local partners and citizen scientists.

Better aligning the CS program to study the impact of nature-based solutions could significantly enhance the existing analytical framework. The NSSID project has implemented various nature-based interventions; however, their hydrological benefits in terms of enhancing water quantity and quality remain undocumented. Considering most upland watersheds are not covered by the traditional hydrometeorological monitoring networks, a CS program provides baseline data and an opportunity to set up hydrological models to quantify the impacts of various interventions. This demands the integration of the CS data with remote sensing and traditional data from EMI and MoWE to increase temporal coverage.

4.4. Capacity-building

The CSts emphasized the need for frequent training and feedback to further improve their understanding of the collected hydrological data and its implications. They suggested enhancing their knowledge transfer capacity and creating a platform for knowledge exchange among citizen scientists, community members, and researchers.

Woreda experts demanded capacity building on hydro-meteorological data analysis and the use of social media platforms for data and information exchange. They also suggested regular workshops to foster knowledge exchange, enhance exposure, and generate knowledge to benefit NbS. The NSSID project partners requested for capacity building to enable them to follow up and support the program and utilize CSts data to inform NbS. They are also interested in enhancing their capacity for identifying river pollution sources involving the CSts to benefit watershed characterization.

4.5. Strategy to sustain the CS program

Program sustainability requires multi-level commitment from CSTs, community, and woreda reflecting the polycentric governance approach (Paul et al., 2018) and careful recruitment of CSTs and para-hydrologists that addresses the participant selection challenges.

Capacity building involving local agricultural and natural resource teams creates the institutional embedding that Bonney et al. (2009) identified as essential for a CS program longevity. Raising local administration awareness fosters the ownership that Buytaert et al. (2014) argue is crucial for community-based monitoring sustainability.

Better linking citizen scientists with the community addresses the social integration challenges that McKinley et al. (2017) highlight as barriers to meaningful environmental engagement. Disseminating CS program findings through multiple communication channels reflects the knowledge-sharing strategies that (Njue et al., 2019) documented as essential for scaling citizen science impact.

However, sustainability ultimately depends on addressing the fundamental resource constraints and institutional capacity limitations that Quinlivan et al. (2020) identified as critical challenges in developing country contexts. While our framework demonstrates promising results, long-term success requires sustained institutional commitment and financial support beyond project timelines - challenges that continue to limit CS potential globally (Conrad & Hilchey, 2011).

The integration of our findings with established CS literature reveals both the promise and limitations of framework-based approaches to hydrological monitoring. While we achieved notable success in participant retention and data collection, the persistent challenges around training, equipment maintenance, and institutional support reflect systemic issues that require continued attention as CS evolves from a novel approach to a mainstream monitoring tool. The framework presented in this study can be customized to the purpose of the CS program, and can be refined by other studies.

4.6. The citizen science framework

The CS framework demonstrated measurable success in data collection, maintaining 78% retention rate of CSTs over several months—exceeding the 60–70% typically reported for citizen science programs (Bonney et al., 2016). This high retention rate validates our framework's effectiveness in addressing key challenges identified in the CS literature, particularly participant engagement and program sustainability (San et al., 2020). The framework allowed knowledge co-generation to enhance future NbS initiatives. However, it can be expanded to enhance the knowledge and experience exchange between citizen scientists, researchers, local district office and NbS projects. CS can serve as a platform to bring together these different actors, blurring the boundary between researchers and non-researchers. Fig. 6 presents a summary of the key outcomes of the discussion during the annual workshop with local partners and citizen scientists.

5. Conclusion

In this study, we developed and tested a citizen science framework consisting of establishment, operational and knowledge generation stages for hydrological monitoring and knowledge co-generation to support nature-based solutions. The following conclusions are drawn based on the study findings:

- This study showed that proper documentation of the steps and activities of community engagement is useful to develop and refine a framework for the establishment and operation of a citizen science program, benefiting expansions of such programs in other watersheds. The framework presented in this study can be customized to other watersheds and purposes.
- The citizen science program provided comprehensive hydrological data of the Kelekindo watershed, including rainfall, river discharge, SGW, and water quality, that would have been difficult to obtain from traditional hydrological agencies.
- The CS data provided a great opportunity to investigate poorly understood hydrological behaviour of the watershed, including the *fill-and-spill* effect due to watershed storage and key characteristics of the hydrograph of an extreme runoff event that revealed the flashy nature of the river flow, requiring sub-daily monitoring engaging a large number of CSTs in the future. Studies need to utilize such understanding of hydrological behavior to inform nature-based solutions.
- Citizen science provides an entry point for meaningful engagement of the community in the identification of nature-based solutions. In Kelekindo, the CSTs were involved in identification, design and site selection of nature-based solutions, showing they are not only data collectors.

Overall, regular discussions and capacity building of the citizen scientists led to an adaptive framework for a CS program, addressing the needs and interests of not only the community but also other stakeholders including para-hydrologists, woreda experts, and project coordinators. The framework's success in maintaining participant engagement while generating scientifically useful data demonstrates the balance between educational and research objectives essential for environmental citizen science sustainability.

CRedit authorship contribution statement

Kirubel Demissie: Writing – review & editing, Visualization, Data curation, Conceptualization. **Hailay Zeray Tedla:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Yirgalem Teshale:** Supervision, Investigation, Data curation. **Gudina Legesse Feyisa:** Writing – review & editing, Validation, Conceptualization. **Amare Hailelassie:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Alemseged Tamiru Haile:** Writing – review & editing, Writing –

original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Tilaye Worku Bekele**: Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Mintamer Ferede**: Writing – review & editing, Visualization, Investigation, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Alemseged Tamiru Haile reports financial support was provided by the Swedish International Development Cooperation Agency (Sida). Amare Haileslassie reports financial support was provided by CGIAR Science Program Scaling for Impact. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the Nature-based Solutions for Sustainable and Inclusive Development (NSSID) program financed by the Swedish International Development Cooperation Agency (Sida) and CGIAR Science Program Scaling for Impact. The NSSID program harnesses the expertise and experience of ten international and national nongovernmental organizations, associations and academic institutions to deliver an ambitious integrated environmental, sustainable development and climate resilience program that will respond to these identified challenges and deliver at scale across Ethiopia. We would like to express our sincere gratitude to both reviewers for their insightful and constructive comments, which greatly strengthened our manuscript by guiding us to add clearer evidence and more detailed explanations.

References

- Aceves-Bueno, E., Adeleye, A. S., Bradley, D., et al. (2015). Citizen science as an approach for overcoming insufficient monitoring and inadequate stakeholder buy-in in adaptive management: Criteria and evidence. *Ecosystems*, 18, 493–506. <https://doi.org/10.1007/s10021-015-9842-4>
- Alves, L. G. S., Da Silva, D. D., Filizola, N. P., & Pruski, F. F. (2017). Stage-discharge relation in non-uniform flow based on Strickler-Manning Equation on amazon basin. *ASABE Annual International Meeting January*. <https://doi.org/10.13031/aim.201700106>
- Azizi, K., Diko, S. K., & Meier, C. I. (2023). A citizen science approach to the characterisation and modelling of urban pluvial flooding. *Water Alternatives*, 16(1), 265–294.
- Babiso, W. Z., Ayano, K. K., Haile, A. T., Keche, D. D., Acharya, K., & Werner, D. (2023). Citizen science for water quality monitoring in the Meki River, Ethiopia: quality assurance and comparison with conventional methods. *Water*, 15, 238. <https://doi.org/10.3390/w15020238>
- Bonney, R., Cooper, C. B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., & Shirk, J. (2009). Citizen science: A developing tool for expanding science knowledge and scientific literacy. *BioScience*, 59(11), 977–984. <https://doi.org/10.1525/bio.2009.59.11.9>
- Bonney, R., Phillips, T. B., Ballard, H. L., & Enck, J. W. (2016). Can citizen science enhance public understanding of science? *Public Understanding of Science*, 25(1), 2–16. <https://doi.org/10.1177/0963662515607406>
- Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., et al. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, 2(October), 1–21. <https://doi.org/10.3389/feart.2014.00026>
- Conrad, C. C., & Hilchey, K. G. (2011). A review of citizen science and community-based environmental monitoring: Issues and opportunities. *Environmental Monitoring and Assessment*, 176(1–4), 273–291. <https://doi.org/10.1007/s10661-010-1582-5>
- Fehri, R., Bogaert, P., Khelifi, S., & Vanclooster, M. (2020). Data fusion of citizen-generated smartphone discharge measurements in Tunisia. *Journal of Hydrology*, 590, Article 125518. <https://doi.org/10.1016/j.jhydrol.2020.125518>
- Ferede, M., Haile, A. T., Walker, D., Gowing, J., & Parkin, G. (2020). Multi-method groundwater recharge estimation at Eshito microwatershed, Rift Valley Basin in Ethiopia. *Hydrological Sciences Journal*, 65(9), 1596–1605. <https://doi.org/10.1080/02626667.2020.1762887>
- Fraisl, D., Campbell, J., See, L., Wehn, U., Wardlaw, J., Gold, M., Moorthy, I., Arias, R., Piera, J., Oliver, J. L., Masó, J., Penker, M., & Fritz, S. (2020). Mapping citizen science contributions to the UN sustainable development goals. *Sustainability Science*, 15(6), 1735–1751. <https://doi.org/10.1007/s11625-020-00833-7>
- Fraisl, D., See, L., Campbell, J., Danielsen, F., & Andrianandrasana, H. T. (2023). The contributions of citizen science to the United Nations sustainable development goals and other international agreements and frameworks. *Citizen Science Theory and Practice*, 8(1), 1–6. <https://doi.org/10.5334/cstp.643>
- Gowing, J., Walker, D., Parkin, G., Forsythe, N., Haile, A. T., & H Ayenew, D. A. (2020). Can shallow groundwater sustain small-scale irrigated agriculture in sub-Saharan Africa? Evidence from N-W Ethiopia. *Groundwater for Sustainable Development*, 10, Article 100290. <https://doi.org/10.1016/j.gsd.2019.100290>
- Haile, A. T., Tedla, H. Z., Mengistie, G. K., Gebre, E. S., Nigusie, L., Haileslassie, A., & Nicol, A. (2025). Applying citizen science to water security challenges in Ethiopia: a structured approach. Colombo, Sri Lanka. *International Water Management Institute, (IWMI)*, 8p. <https://hdl.handle.net/10568/173480>
- Haklay, M. (2015). *Citizen Science and Policy: A European Perspective*. Washington, DC: Woodrow Wilson International Center for Scholars.
- Hulluka, T. A., Ebrahim, G. Y., Haile, A. T., & Haileslassie, A. (2024). Shallow groundwater potential mapping and evaluation for climate resilient smallholder irrigation in the Zeway-Shalla Sub-basin, Ethiopia. *Groundwater for Sustainable Development*, 27, Article 101367. <https://doi.org/10.1016/j.gsd.2024.101367>
- Jollymore, A., Haines, M. J., Satterfield, T., & Johnson, M. S. (2017). Citizen science for water quality monitoring: Data implications of citizen perspectives. *Journal of Environmental Management*, 200(2017), 456–467. <https://doi.org/10.1016/j.jenvman.2017.05.083>
- Jordan, R., Gray, S., Sorensen, A., Newman, G., Mellor, D., Newman, G., et al. (2016). Studying citizen science through adaptive management and learning feedbacks as mechanisms for improving conservation. *Conservation Biology*, 30(3), 488–495. <https://doi.org/10.1111/cobi.12659>
- Little, K. E., Hayashi, M., & Liang, S. (2016). Community-based groundwater monitoring network using a citizen-science approach. *Groundwater*, 54(3), 317–324. <https://doi.org/10.1111/gwat.12336>
- Loghmani-Khouzani, T., Dany, V., Seifert, N., Madani, K., & Guenther, E. (2024). Can citizen science in water-related nature-based solutions deliver transformative participation in agri-food systems? A review. *Agricultural Systems*, 220, Article 104052. <https://doi.org/10.1016/j.agsy.2024.104052>
- McKinley, Miller-Rushing, D. C., Ballard, A. J., Bonney, H. L., Brown, R., Cook-Patton, H., et al. (2017). Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation*, 208, 15–28. <https://doi.org/10.1016/j.biocon.2016.05.015>
- Mengistie, G. K., Demissie, W. K., Walker, D. W., & Haile, A. T. (2024). Value of quality controlled citizen science data for rainfall-runoff characterization in a rapidly urbanizing catchment. *Journal of Hydrology*, 629, Article 130639. <https://doi.org/10.1016/j.jhydrol.2024.130639>
- Nardi, F., Cudennec, C., Abrate, T., Allouch, C., Annis, A., Assumpção, T., Aubert, A. H., Béro, D., Braccini, A. M., Buytaert, W., Dasgupta, A., Hannah, D. M., Mazzoleni, M., Polo, M. J., Sæbø, Ø., Seibert, J., Tauro, F., Teichert, F., Teutonic, R., ... Grimaldi, S. (2022). Citizens AND Hydrology (CANDHY): conceptualizing a transdisciplinary framework for citizen science addressing hydrological challenges. *Hydrological Sciences Journal*, 67(16), 2534–2551. <https://doi.org/10.1080/02626667.2020.1849707>

- Nath, S., & Kirschke, S. (2023). Groundwater monitoring through citizen science: A review of project designs and results. *Groundwater*, 61(4), 481–493. <https://doi.org/10.1111/gwat.13298>
- Nigussie, L., Bekele, T. W., Haile, A. T., Mdee, A., Nicol, A., Cohen, J., Osei-Amponsah, C., Tedla, Z. H., & Demissie, K. (2025). Does a citizen science approach enhance the effectiveness of flood early warning systems? Evidence from the Akaki Catchment, Ethiopia. *Citizen Science Theory and Practice*, 10(1), 1–14. <https://doi.org/10.5334/cstp.763>
- Nigussie, L., Barron, J., Haile, A. T., Lefore, N., & Gowing, J. (2018). *Gender dimensions of community-based groundwater governance in Ethiopia: using citizen science as an entry point*, 24 Colombo, Sri Lanka: International Water Management Institute (IWMI), (IWMI Working).
- Njue, N., Stenfort Kroese, J., Gräf, J., Jacobs, S. R., Weeser, B., Breuer, L., & Rufino, M. C. (2019). Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects. *Science of the Total Environment*, 693. <https://doi.org/10.1016/j.scitotenv.2019.07.337>
- Paul, J. D., Buytaert, W., Allen, S., Ballesteros-Canovas, J. A., Bhusal, J., Cieslik, K., Clark, J., Dugar, S., Hannah, D. M., Stoffe, M., Dewulf, A., Dhita, M. R., Liu, W., Nayava, J. L., Neupane, B., Schiller, A., Smith, P. J., & Supper, R. (2018). Citizen science for hydrological risk reduction and resilience building. *Wiley Interdisciplinary Reviews: Water*, 5(1), 1–15. <https://doi.org/10.1002/WAT2.1262>
- Quinlivan, L., Chapman, D. V., & Sullivan, T. (2020). Validating citizen science monitoring of ambient water quality for the United Nations sustainable development goals. *Science of the Total Environment*, 699, Article 134255. <https://doi.org/10.1016/j.scitotenv.2019.134255>
- San, A., Capdevila, L., Kokimova, A., Sinha, S., Avellán, T., Kim, J., & Kirschke, S. (2020). Success factors for citizen science projects in water quality monitoring. *Science of the Total Environment*, 728, Article 137843. <https://doi.org/10.1016/j.scitotenv.2020.137843>
- Starkey, E., Parkin, G., Birkinshaw, S., Large, A., Quinn, P., & Gibson, C. (2017). Demonstrating the value of community-based ('citizen science') observations for catchment modelling and characterisation. *Journal of Hydrology*, 548, 801–817. <https://doi.org/10.1016/j.jhydrol.2017.03.019>
- Staudinger, M., Stoelzle, M., Seeger, S., Seibert, J., Weiler, M., & Stahl, K. (2017). Catchment water storage variation with elevation. *Hydrological Processes*, 31, 2000–2015. <https://doi.org/10.1002/hyp.11158>
- Taye, M. T., Ebrahim, G. Y., Nigussie, L., Hagos, F., Uhlenbrook, S., & Schmitter, P. (2022). Integrated water availability modelling to assess sustainable agricultural intensification options in the Meki Catchment, Central Rift Valley, Ethiopia. *Hydrological Sciences Journal*, 67(15), 2271–2293. <https://doi.org/10.1080/02626667.2022.2138403>
- Tedla, H. Z., Bekele, T. W., Nigussie, L., Negash, E. D., Walsh, C. L., O'Donnell, G., & Haile, A. T. (2024). Threshold-based flood early warning in an urbanizing catchment through multi-source data integration: Satellite and citizen science contribution. *Journal of Hydrology*, 635, Article 131076. <https://doi.org/10.1016/j.jhydrol.2024.131076>
- Tedla, H. Z., Haile, A. T., Walker, D. W., & Melesse, A. M. (2022). Evaluation of factors affecting the quality of citizen science rainfall data in Akaki catchment, Addis Ababa, Ethiopia. *Journal of Hydrology*, 612, Article 128284. <https://doi.org/10.1016/j.jhydrol.2022.128284>
- Tran, H. N., Rutten, M., Prajapati, R., Tran, H. T., Duwal, S., Nguyen, D. T., Davids, J. C., & Miegel, K. (2024). Citizen scientists' engagement in food risk-related data collection: A case study in Bui River Basin, Vietnam. *Environmental Monitoring and Assessment*, 196, 280. <https://doi.org/10.1007/s10661-024-12419-2>
- Upreti, M., Ochoa-Tocachi, B., F., Paul, J. D., Regmi, S., & Buytaert, W. (2019). Improving water resources management using participatory monitoring in a remote mountainous region of Nepal. *Journal of Hydrology Regional Studies*, 23, Article 100604. <https://doi.org/10.1016/j.ejrh.2019.100604>
- Walker, D., Forsythe, N., Parkin, G., & Gowing, J. (2016). Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme. *Journal of Hydrology*, 538, 713–725. <https://doi.org/10.1016/j.jhydrol.2016.04.062>
- Walker, D., Haile, A. T., Gowing, J., Legesse, Y., Gebrehawariat, G., Hundie, H., Berhanu, D., & Parkin, G. (2019). *Guideline: Community-based hydroclimate monitoring. REACH Working Paper 5*. Oxford, UK: University of Oxford 2019.
- Weeser, B., Stenfort Kroese, J., Jacobs, S. R., Njue, N., Kemboi, Z., Ran, A., Rufino, M. C., & Breuer, L. (2018). Citizen science pioneers in Kenya – A crowdsourced approach for hydrological monitoring. *Science of the Total Environment*, 631–632, 1590–1599. <https://doi.org/10.1016/j.scitotenv.2018.03.130>