CITIZEN SCIENCE:
THEORY AND PRACTICE

Does a Citizen Science Approach Enhance the Effectiveness of Flood Early Warning Systems? Evidence from the Akaki Catchment, Ethiopia

RESEARCH PAPER

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ABSTRACT

Flooding has emerged as a significant concern in the Akaki catchment area of Ethiopia, affecting settlements and properties. Early warning systems (EWSs) are implemented to reduce flood risks, but power dynamics among at-risk communities and stakeholders have raised concerns about the reliable accessibility of warning information. We integrated a citizen science approach into existing flood EWSs to promote inclusivity, local perspectives, and equitable expertise distribution in flood early warning. It draws on primary data collected through diverse methods, alongside an extensive review of documents from the years 2021 to 2022. The analysis of qualitative data indicates the integration of citizen science into a flood EWSs delivers dependable early warning information and encourages the establishment of networks. This approach reduces dependence on external entities, enhances local decision-making capabilities, and promotes a sense of ownership, empowerment, and trust. This can transform the dynamics and responsibilities linked to flood management. However, the longer-term participation of citizen scientists in flood EWSs is challenging due to the disparity between commitment levels and benefits, lack of legal frameworks, and insufficient recognition of community diversity within policy frameworks. The research herein emphasizes the significance of understanding power dynamics and institutional capacities in integrating citizen science into flood EWSs. It offers valuable perspectives for policymakers, practitioners, and communities on participatory governance, social equity, and the resilience of communities in the face of environmental challenges.

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KEYWORDS:
citizen science; community-based flood early warning system; disaster risk management; power dynamics; Akaki catchment area; Ethiopia

TO CITE THIS ARTICLE:
Nigussie, L, Bekele, TW, Haile, AT, Mdee, A, Nicol, A, Cohen, J, Osei-Amponsah, C, Tedla, ZH and 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): 9, pp. 1–14. DOI: https://doi.org/10.5334/cstp.763

INTRODUCTION

Natural disasters have been increasing globally from 1960 to 2018 (Buszta et al. 2023), with flooding being the most common natural disaster impacting millions of people annually, resulting in 6,000 to 18,000 deaths (Vaidya et al. 2023). The risk of hydrometeorological hazards like floods is on the rise (Norizan et al. 2021), particularly affecting vulnerable populations such as marginalized households (Hino and Nance 2021). Low- and middle-income countries account for 89% of the population exposed to floods, with 44% living in extreme poverty in Sub-Saharan Africa (Rentschler, Salhab, and Jafino 2022). A comprehensive flood risk–reduction strategy is essential to enhance preparedness, mitigate risks, reduce vulnerability, and improve disaster response (Norizan et al. 2021). Early warning systems (EWSs) play a crucial role in disaster risk management, especially in minimizing the impact of floods (Shah et al. 2023).

The United Nations International Strategy for Disaster Reduction defines an EWS as a multifaceted system comprising risk assessment, forecasting, communication, and preparedness (UNISDR 2016). Community-based approaches are highlighted (Khan et al. 2018) to address flooding causes, and promote inclusivity and local ownership (Gyawali et al. 2021). Citizen science, a global volunteer-based method (Marchezini et al. 2018), plays a vital role in environmental monitoring and disaster management (Hicks et al. 2019). Through 106 cases of citizen science applied to disaster risk reduction across all continents, it has shown potential in generating actionable knowledge for early warnings and impact assessments (Hicks et al. 2019).

In flood EWSs, citizen science involves local volunteers collaborating with professionals and agencies to collect and analyze flood risk data (See 2019) using inexpensive sensors, monitoring networks (Gautam and Phaiju 2013), participatory mapping, and modeling (Pandeya et al. 2021). Many citizen science projects depend on a small percentage of participants to generate most contributions (Laut et al. 2017). This approach fosters equitable distribution of expertise and decision-making power (Walker, Smigaj, and Tani 2021), ultimately improving the efficiency of EWS by evolving it into a community-based early warning system (CBEWS).

The concept of a CBEWS highlights the crucial role of community participation in understanding flood hazards, monitoring and warning, effective communication, and prompt response (UNISDR 2009). However, challenges arise when there is a mismatch between knowledge holders and decision-makers (McLindin 2019). Power imbalances and varying capabilities among actors can lead to unequal resource allocation and exclusion of marginalized groups in decision-making (Bajracharya et al. 2021), hindering local engagement and system effectiveness (Chinguwo and Deus 2022). It is crucial to address these issues for a more inclusive, equitable, and sustainable EWS.

Despite the potential, EWS efforts often prioritize system development over understanding citizens' needs and engagement techniques (Sufri et al. 2020). Limited research exists on the involvement of local actors in EWS elements (Gautam and Phaiju 2013), and practical evidence of citizen engagement in CBEWS is scarce. To fill this gap, we employ Amartya Sen's Capability Approach framework (Sen 1999), which emphasizes a participatory approach, agency, and the expansion of local capabilities.

Our study focused on analyzing citizen engagement in the Akaki flood EWSs in Ethiopia, specifically examining power dynamics. We conducted action research in the Akaki catchment area due to concerns, which include lack of reliability of warning information and insufficient collaboration among stakeholders, raised by flood-prone communities regarding the formal flood EWSs. These concerns point towards the ineffectiveness of the formal system, driven by existing power imbalances. Hence, this study aimed to answer the following questions:

How does the interplay of power affect the participation and resource access of local actors in flood EWSs in the Akaki catchment area?

How does the use of a citizen science approach influence the participation and resource access of local volunteers and/or their collaboration with other stakeholders?

What factors influence the success of a citizen science approach in addressing power dynamics in flood EWSs?

Specifically, this study investigated the impact of involving citizen scientists in the flood EWSs of the Akaki catchment. It focused on three main aspects: (1) engagement and interaction, (2) resource availability and accessibility, and (3) information sharing. The goal is to transform power dynamics within the four elements of the flood EWS—risk knowledge, monitoring and warning, communication and dissemination, and response capability—thereby enhancing the overall effectiveness of the system. Herein, we offer wider evidence regarding the potential and challenges of applying citizen science to address power dynamics in EWSs. We outline the method by describing the study area, presenting the conceptual framework, and detailing the data collection methods and analysis. We then present the results and discussion followed by conclusions with practical implications.

POTENTIALS AND CHALLENGES OF APPLYING CITIZEN SCIENCE FOR ADDRESSING POWER DYNAMICS IN FLOOD EARLY WARNING SYSTEMS

Citizen science can empower local communities in disaster risk reduction by addressing power dynamics in the four flood EWS elements. In the *risk knowledge* element, citizen science may enhance deliberation among diverse stakeholders through transdisciplinary collaboration (Andress et al. 2020), a valuable resource for researchers and decision-makers to explore local perspectives on floods. For example, in the Banjarnegara and Wonosobo districts of Indonesia, integrating citizen science into a flood EWS aimed to develop community-based rainfall data management (Nugroho 2022). This approach improved the accuracy of rainfall measurements, enhanced students' understanding of natural sciences, and increased community literacy regarding floods and their mitigation (Nugroho 2022). Additionally, it empowers locals to advocate for flood early warning needs (Walker, Smigaj, and Tani 2021), promoting inclusive disaster preparedness and response.

In the *monitoring and warning* element, building citizen scientists' capacity to monitor risks reduces dependency on external authorities while enabling local actions (Wilson et al. 2018). Low-cost sensors (Pandeya et al. 2021) and participation techniques help collect real-time data (Tedla et al. 2022) for predicting disasters and issuing warnings. For example, citizen science-based hydrological monitoring in Nepal's Karnali River Basin used low-cost sensors, increasing data coverage and empowering locals to improve flood resilience (Pandeya et al. 2021). Citizen observatories can lower flood damage costs by combining citizen data with hydrological models (Ferri et al. 2019). Success depends on clear procedures, communication, and local support (Le Coz et al. 2016). Such approaches give citizen scientists a sense of ownership and agency in addressing local challenges, thereby challenging existing power dynamics that may marginalize local voices (Wehn et al. 2015). In the *dissemination and communication* element, citizen science and community flood monitoring initiatives boost social capital, improve risk communication (Wolff 2021), and enhance local engagement (Pocock et al. 2019; Gyawali et al. 2021). This can lead to a more balanced exchange of warning information. However, challenges remain in achieving equal participation and collaboration between scientists and citizen scientists (Cheung and Feldman 2019). In the *response capability* element, citizen science enhances the engagement of at-risk local actors and institutions in both normal and emergency situations to improve their response capabilities (Cheung and Feldman 2019). For example, in Senegal, by employing participatory downscaling and integrating local knowledge, Kniveton et al. (2015) created weather forecasts tailored for flood-prone areas to enable farmers to make informed cropping decisions, which led to enhanced yields and contributed to the preservation of lives and livelihoods during flood events.

Citizen science plays a crucial role in addressing power dynamics in community development; however, it encounters various challenges. One significant challenge is ensuring the inclusion of diverse participants and representation in communities characterized by power imbalances. This often proves difficult, as it can lead to elite capture and the deliberate abandonment of responsibilities by other institutions (Boesten, Mdee, and Cleaver 2011). Additionally, adequate allocation of resources becomes a challenge when funding is scarce and competing priorities exist (Chinguwo and Deus 2022). To sustain citizen involvement, it is essential to evaluate volunteer interests (Kasten, Jenkins, and Christofoletti 2021). Government agencies may resist citizen science initiatives if strong partnerships are lacking (Walker, Smigaj, and Tani 2021). Furthermore, early enthusiasm for citizen science projects may wane over time, making it crucial to assess motivations. Trust and transparency issues also arise in EWSs due to uncertainties and failures (Marchezini et al. 2018).

METHODS

STUDY AREA

This study was conducted in downstream areas of the Akaki catchment areas (Figure 1), which is upstream of Awash River Basin of Ethiopia (Shibeshi et al. 2019). The Akaki catchment in Ethiopia comprises the Little and Big Akaki watersheds, converging at the Aba-Samuel reservoir. This area experiences significant precipitation from June to September, with August averaging an annual rainfall of 1,114.9 mm (Guyasa, Guan, and Zhang 2023). Flooding presents a critical challenge in the Akaki catchment, with frequent flood events between the months of May and November (Bekele et al. 2022). The predominant land use in this catchment is agricultural (Guyasa, Guan, and Zhang 2023).

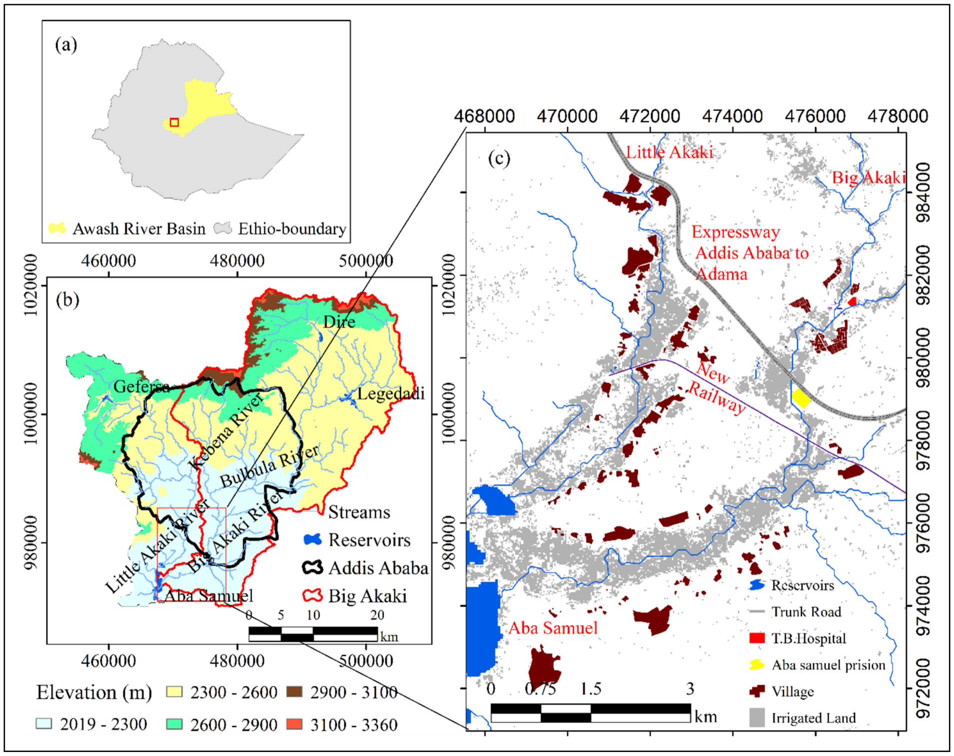

Figure 1 Map of the study area. **(a)** The Akaki catchment location in the Ethio-boundary and Awash River Basin (red rectangle), **(b)** The elevation and Big-Akaki sub-catchment, **(c)** The study location.

CONCEPTUAL FRAMEWORK

Our conceptual framework is based on Amartya Sen's Capability Approach (Sen 1999). Figure 2 illustrates how Amartya Sen's Capability Approach framework (Sen 1999) was utilized to analyze the impact of integrating citizen science in flood EWSs on power dynamics. Sen's Capability Approach framework offers a comprehensive tool for understanding the complexities of power dynamics by emphasizing human capabilities, agency (Ton et al. 2021), and social justice. It provides valuable insights for improving community resilience and promoting equitable flood management practices. Additionally, the framework advocates for a participatory approach to development, highlighting the importance of agency, democracy, freedom, and the expansion of local people's capabilities (Hammock 2019).

We used this framework to examine how integrating citizen science in flood EWSs affects power dynamics. It focused on changes in citizen scientists' participation,

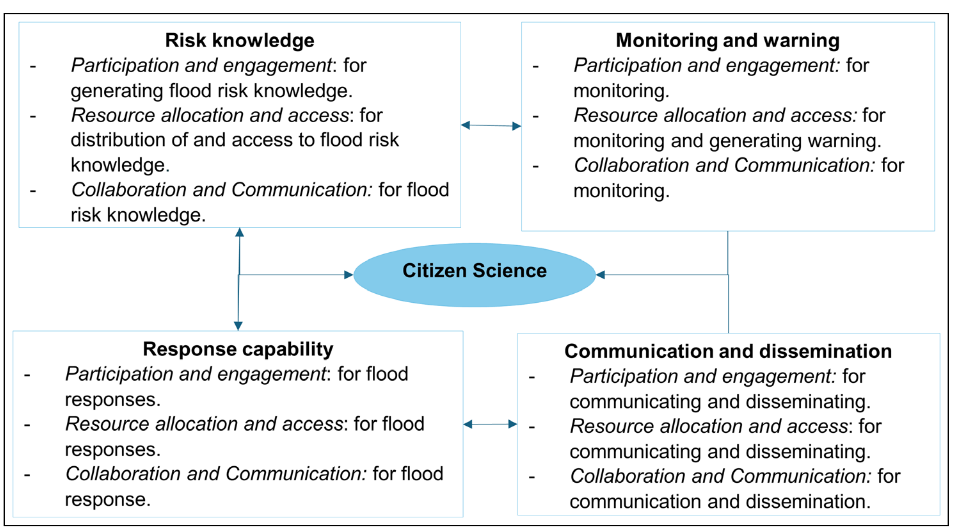

Figure 2 Framework for analysis of power dynamics in community-based flood early warning system (CBFEWS) using citizen science approach (Modified after Sen 1999).

resource allocation, collaboration, and communication abilities. We examined how citizen science initiatives impact knowledge acquisition, critical thinking, problem-solving, and decision-making in addressing flood risks. We also looked at how citizen science improves citizen scientists' skills in monitoring, warning, communicating and disseminating, and responding (locally) to floods.

It is important to acknowledge some limitations. The approaches were tested only in the Akaki catchment area and have yet to be applied in other contexts within Ethiopia and more globally. Furthermore, further research is needed to explore incentives for engaging citizen scientists in flood EWSs. The unit of our analysis is individual citizen scientists.

COMMUNITY ENGAGEMENT IN FLOOD EARLY WARNING SYSTEMS IN ETHIOPIA

Ethiopia's Disaster Risk Management Policy highlights the significance of EWSs in preventing harm (FDRE 2013). The policy promotes a decentralized approach involving collaboration between government, organizations, communities, and individuals. While the policy does not explicitly define communities, it emphasizes they play a vital role by sharing information on hazards and responding to warnings (FDRE 2013).

DATA COLLECTION

Figure 3 illustrates the methods used to collect data for the study, presented in three phases. Primary data was gathered through methods such as observation, interviews, and workshops over a 22-month period in 2021–2022, with oral consent obtained from citizen participants. This method of obtaining consent was chosen to build trust and strengthen relationships, as individuals tend to feel more comfortable and trusting in verbal communication. The study protocol was reviewed and approved by the project management team and the project's ethics committee member to meet ethical standards. The study also utilized data obtained from various secondary sources including academic journals and reports collected through online databases such as JSTOR to understand concepts focusing on citizen science, CBEWS, power dynamics, and EWSs. Both primary and secondary data were collected in three phases of integrating citizen science into flood EWSs: pre-community-based flood early warning systems (CBFEWSs), co-designing CBFEWSs, and co-testing CBFEWS.

Pre-community-based flood early warning systems

In February 2021, researchers from the International Water Management Institute (IWMI) and Addis Ababa University (AAU) began a study on flood risk in the Akaki catchment area. The team, consisting of hydrologists and a social scientist, used systems thinking to analyze flood factors. They reviewed flood risk management documents and conducted a scoping study in March 2021, by performing transect walks and having discussions with people from at-risk communities which revealed that intense rain runoff and Legedadi dam water discharge posed major flood threats. The formal flood EWSs by the Addis Ababa Water and Sewerage Authority (AAWSA) and Ethiopian Meteorological Institute (EMI) lacked community engagement, leading at-risk communities to rely on informal networks for flood information. The team

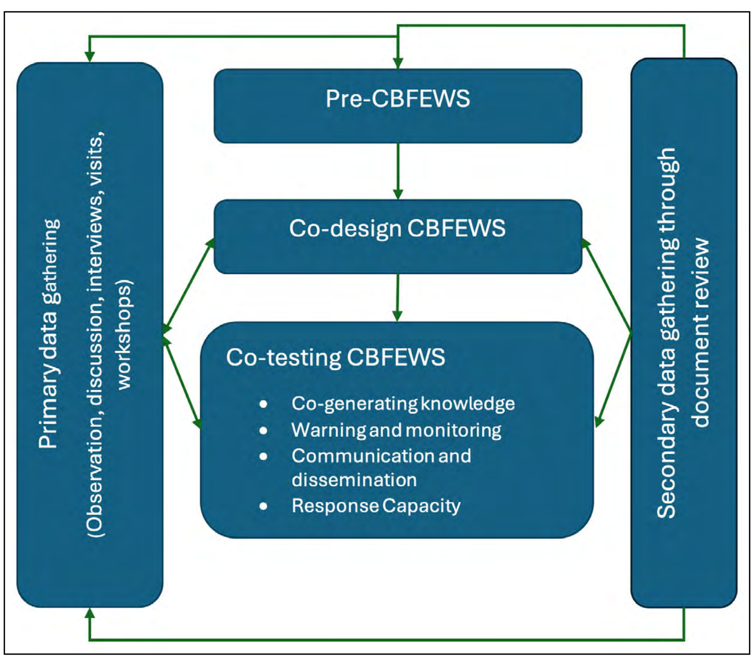

Figure 3 Data collection methods in three phases.

emphasized the need to involve key stakeholders like at-risk communities in the formal flood EWSs to enhance overall effectiveness.

To enhance understanding of the flood risk–management context in Akaki, the research team conducted six focus group discussions (FGDs) and key informant interviews (KIIs) to gather primary data. These FGDs involved men and women from at-risk communities and aimed to understand their socio-economic conditions, knowledge of flood risks, and participation in EWSs. The six FGDs consisted of three groups of men and three groups of women from diverse social backgrounds, each with a maximum of eight participants. Participants from at-risk communities were selected based on age, gender, geographic location, and livelihood activities. The discussions were guided by a semi-structured questionnaire, focusing on dominant livelihood activities, perceptions of flood risks, access to early warning information, and participation in the EWSs.

In addition, 10 key informants from key stakeholder institutions were identified using snowball sampling (Hesse-Biber 2012). These informants were from AAWSA, EMI, AAU, IWMI, the Red Cross, the Fire and Emergency Office, and the Akaki-Kaliti sub-city. The objective of the KIIs was to gain insights into the participants' roles in flood risk management, along with their perceptions regarding flood risks, accessibility to early warning information, and the level of community involvement in both flood risk management and the EWSs. The interviews followed a semi-structured questionnaire divided into modules focusing on perceptions of flood risks, the roles of different community groups residing in flood-prone areas, and the multi-level participation mechanisms used to engage local people in flood risk management and EWSs.

Co-designing community-based flood early warning systems

Drawing on collaboratively generated knowledge and the flood risk management document review, the team of researchers, people from at-risk communities involved in the transect walk, along with experts from EMI and AAWSA reached to a consensus to add a citizen science element in the existing flood EWSs to improve reliability of the early warning information (Bekele et al. 2022; Tedla et al. 2022; Alemu et al. 2023; Mengistie et al. 2024; Tedla et al. 2024) by pursuing the following steps.

A total of eleven citizen scientists (6 women, 5 men) were identified by researchers and community members who participated in the transect walk. In this study, we defined a citizen scientist as a volunteer from an at-risk community who engages with stakeholders involved in the flood EWSs to co-generate knowledge on flood risks, manage environmental conditions, and disseminate relevant information. To ensure diversity, citizen scientists were selected from three locations within the catchment area representing different social backgrounds in terms of gender, age, and geographic location. Their socio-economic profiles are detailed in Table 1, with "young" referring to individuals under 35 and "well off" to those generating seasonal income through farming. Those relying on daily wages or not engaged in any livelihood activities are classified as "resource poor." The team limited the number of citizen scientists to enhance coordination, reduce costs, ensure commitment, and build trust within the community while designing the CBFEWSs.

Co-testing of the community-based flood early warning systems

Different stakeholders were involved in the CBFEWS, and each played a unique role in co-testing the

GEOGRAPHIC LOCATION	GENDER	AGE	WEALTH STATUS	LIVELIHOOD ACTIVITY
Upstream of Tirunesh Beijing hospital	M	<35	Resource poor	Playing fooball
	M	≥35	Well off	Farming
	F	≥35	Resource poor	Managing household activities
	M	<35	Resource poor	Sand mining
Areas between Tirunesh Bejing hospital and the expressway	F	<35	Resource poor	Wage employment
	F	≥35	Well off	Farming
	M	<35	Resource poor	Sand mining
	M	≥35	Well off	Farming
Downstream of the express expressway	F	<35	Resource poor	Wage employment
	F	<35	Well off	Farming
	F	≥35	Well off	Farming

Table 1 Socio-economic profile of citizen scientists.

system. The specific roles of each stakeholder within the four components of the CBFEWS (co-generating knowledge, monitoring and warning, communicating and disseminating, and enhancing response capabilities of at-risk communities), with citizen scientists identified as pivotal actors in this process, are outlined below. Figure 4 illustrates the relationship amongst key CBFEWS stakeholders in the Akaki catchment.

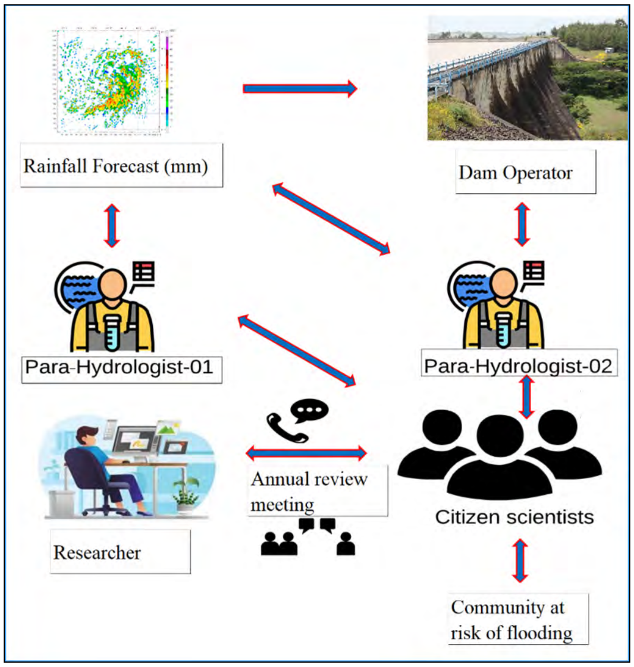

Figure 4 Relationships amongst community-based flood early warning system (CBFEWS) stakeholders (Adapted from Tedla et al. 2023).

Co-generating knowledge – In an effort to enhance the involvement of citizen scientists in the co-generation of knowledge, researchers from the IWMI implemented a range of supportive initiatives, including journal-keeping, site visits, and training workshops. In April 2021, all eleven citizen scientists engaged in a training program that emphasized the significance of keeping journals. Participants were provided with journals, pens, and instructions for journaling about flooding. They were encouraged to record dates, times, impacts, causes, and sources of flood early warnings to improve understanding and identify system improvements. Two IWMI hydrologists acted as para-hydrologists, providing technical support, facilitating communication among stakeholders, and reviewing journals for insights.

IWMI organized visits to Legedadi dam and EMI for citizen scientists, as well as stakeholder meetings for networking and knowledge sharing.

Monitoring and warning – To increase the involvement of citizen scientists in the monitoring and warning element, hydrologists from the IWMI and AAU conducted training for two young male citizen scientists to oversee the water levels of the Akaki River and analyze rainfall predictions for the purpose of issuing flood alerts. The training was exclusively offered to young men due to the belief that older individuals lacked energy for monitoring, while women preferred less demanding roles like information sharing. The citizen scientists were provided airtime for phone calls, text messages, and data services on their mobile devices; umbrellas; and boots for work.

Communication and dissemination – To improve communication and the dissemination of information, two citizen scientists were designated to collect early warning data from the operator of the Legedadi dam and the EMI for the purpose of communication. They obtained flood alerts from the dam operators via mobile communication when water levels reach critical thresholds and actively participated in a Telegram channel operated by the EMI providing rainfall forecasts.

Finally, we carried out interviews with seven participants (including three women and four men) at the end of the 2022 rainy season. The purposes of the interviews were to explore how engagement in the flood EWSs influenced citizen scientists' participation in knowledge co-creation and in the decision-making processes and their access to vital resources influenced their capabilities to generate and disseminate warning information. We also examined the advantages and obstacles encountered by citizen scientists when participating in the CBFEWS.

DATA ANALYSIS

All interviews, FGDs, and journaling conducted by citizen scientists were carried out in Amharic. These were then recorded, transcribed, translated into English, and analyzed.

We employed manual thematic coding and content analysis, as outlined by Krippendorff (2018) to thoroughly analyze primary and secondary qualitative data. The analysis identified three main themes for each of the four elements of the CBFEWS: participation and engagement, resource allocation and access, and collaboration and communication. Regarding participation and engagement, the study analyzed how citizen scientists' and other stakeholders' involvement in activities such as research, meetings, documentation, monitoring, and communication influenced their capabilities. In terms of resource allocation and access, the study explored how the availability and distribution of crucial resources, including knowledge, information, and networks, impacted citizen scientists' capabilities. Lastly, the study examined how interactions between citizen scientists and other stakeholders influenced their capabilities under the theme of collaboration and communication.

RESULTS AND DISCUSSION

The damage caused by flooding in the Akaki catchment area prompted implementation of EWSs to enhance community response capabilities. Our findings indicate there are currently two EWSs in operation: a formal one involving professional stakeholders from relevant institutions such as AAWSA, EMI, and the Red Cross, and an informal system managed by vulnerable communities. Concerns have been raised regarding the reliability of and lack of community involvement in the formal systems, which is driven by power imbalances within EWSs. To address these concerns, the citizen science approach was integrated in the formal EWSs. This study examined the impact of community involvement in flood EWSs on power dynamics within the four elements of the system with a specific focus on participation, resource allocation, collaboration, communication, and the associated benefits and challenges. Figure 5 illustrates a framework for building flood risk resilience at the local level.

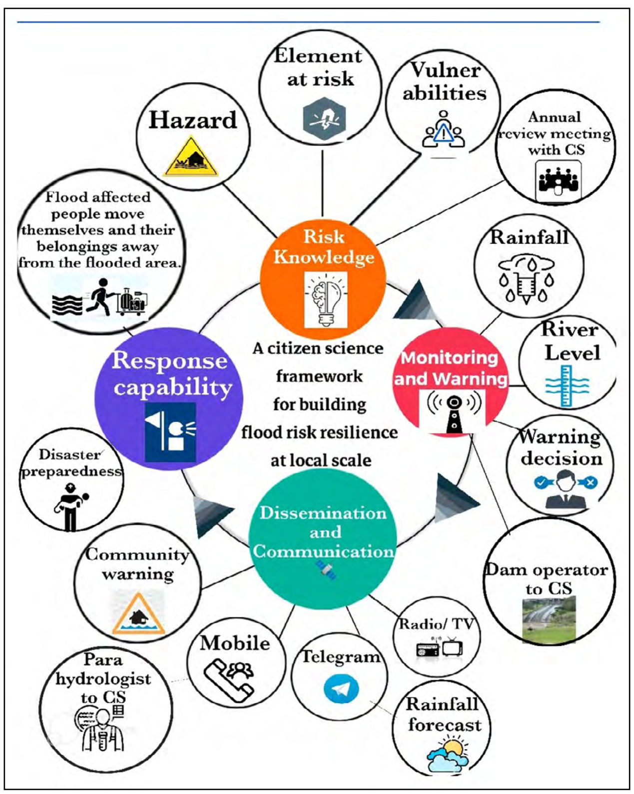

Figure 5 A citizen science framework for building flood risk resilience at the local level (Adapted from Tedla et al. 2023).

RISK KNOWLEDGE

Our results show the Fire and disaster Commission along with similar organizations play a crucial role in developing flood risk knowledge for intervention strategies. However, lack of involvement from stakeholders like Legedadi dam operators and at-risk communities, plus limited access to this knowledge, hinders resilience efforts for vulnerable populations. As suggested in various studies, the adoption of a citizen science framework has emerged as a viable solution to this challenge (Khan et al. 2018; Gyawali et al. 2021; Marchezini et al. 2018; Hicks et al. 2019).

By implementing this framework, citizen scientists and stakeholders have become actively involved in the EWSs for floods in Akaki. This approach has facilitated collaboration among citizen scientists and various stakeholders through site visits, training sessions, documentation efforts, and participation in meetings, thereby empowering them to gain risk-related knowledge pertinent to the catchment area.

The partnerships between citizen scientists and other stakeholders also enhanced citizen scientists' critical thinking, problem-solving, and decision-making skills. For example, collaboration with rainfall forecasters helped citizen scientists learn about rainfall forecasting and assess the effects of heavy rainfall in areas of Addis Ababa such as Arat Kilo, Ayat, Megenagna, Entoto, and Sidist Kilo, on local flooding. Additionally, researchers from the IWMI conducted training sessions aimed at enabling citizen scientists to convert rainfall forecasts into flood forecasts. One citizen scientist expressed his newfound understanding by saying:

> "*This year, we learned from researchers that the amount of water released from the Legedadi dam alone will not cause damage unless it combines with runoff from heavy rainfall from areas of Addis Ababa. This is because the flood from rain increases the pressure and water level of the Akaki River.*"

The collaborative strategy significantly enhanced communication among stakeholders, particularly through the visits of citizen scientists to the Legedadi dam and the EMI. The visits to the Legedadi dam provided citizen scientists with insights into a range of factors that affect water release from the dam and its structural design, thereby clarifying misconceptions about the impact on flooding. Additionally, citizen scientists found that the narrow stream channel guiding water through the bottom outlet of the dam does not cause significant flooding downstream. Better communication between citizen scientists and dam operators has led to reduced nighttime flooding from dam discharges, assisting vulnerable communities in evacuation and property protection during floods. This cooperation has empowered at-risk communities to request help, and aligns with Walker, Smigaj, and Tani (2021), who highlighted that citizen science helps at-risk communities voice their flood-warning needs, promoting inclusive disaster readiness and response.

The participation of citizen scientists in the collaborative generation of knowledge has made substantial contributions to the comprehension of flood risk. This aligns with the assertion that citizen science can ease deliberation among various stakeholders through transdisciplinary collaboration (Andress et al. 2020), serving as an asset for researchers and policymakers to investigate local viewpoints on flooding. For instance, journaling enabled citizen scientists to enhance their understanding of potential flooding triggers and the effects of heavy rainfall and dam water releases on local flood events. Specifically, citizen scientists found that an overflow of the Kebena River, intensified by runoff from heavy rainfall and dam water discharge, could result in flooding in their area within a 12-hour period. Additionally, the collaboration between citizen scientists and researchers from the IWMI and AAU has provided citizen scientists with critical insights into the relationship between water discharge from the Legedadi dam and the depth and extent of flooding in their locality. The collective knowledge was further enriched through shared insights from citizen scientists and stakeholders during meetings, site visits, and direct interactions. However, it is noteworthy that, despite the opportunity for eleven citizen scientists to engage in journaling, only four individuals (three men and one woman) consistently recorded their observations. The other participants faced challenges such as illiteracy, time constraints, and a preference for other aspects of the CBFEWS over journaling.

In summary, the engagement of citizen scientists in the Akaki flood EWSs—through collaboration, visits, trainings, and participation in meetings—enhanced their access to information and knowledge. This engagement has significantly improved their critical thinking, problem-solving, and decision-making skills. It also provided them with the opportunity to actively take part in the process of knowledge co-generation.

MONITORING AND WARNING

Studies show building citizen scientists' capacity to monitor risks through low-cost sensors and participation techniques enables the collection of real-time data for disaster prediction and warnings while empowering citizen scientists (Pandeya et al. 2021); this then leads to reduced reliance on external authorities (Wilson et al. 2018) and flood damage costs (Ferri et al. 2019). Results from our analysis also showed the same, revealing that engagement of citizen scientists in the flood EWSs enabled them to gain access to training aimed at advancing their skill for monitoring and interpreting data. For example, the training offered by researchers from the IWMI and AAU to two young male citizen scientists on estimating runoff from rainfall forecasts significantly enhanced their skills in generating flood forecasts, which reduced the need for constant communication with dam operators. One citizen scientist expressed his appreciation for the training as:

> *"This year, we received valuable instruction from IWMI and AAU researchers on how to calculate changes in water level at the Legedadi dam using three-day rain forecasts from the EMI and rainfall intensity data from the citizen science monitoring network. This knowledge has reduced the number of calls we need to make to the dam operators to obtain warning information."*

DISSEMINATION AND COMMUNICATION

In the context of dissemination and communication, we investigated how the involvement of citizen scientists in the flood EWSs influences the strategies employed by community members and local institutions to communicate flood risks and alerts. We also assessed changes in dependability, accessibility, and reachability of warning messages. Accordingly, the qualitative data analysis revealed that the incorporation of citizen science within the Akaki flood EWSs has markedly enhanced the communication capabilities and the credibility and accessibility of warning messages.

Before the active participation of community members, the EWSs functioned within a hierarchical communication structure that hindered vulnerable communities from effectively preparing for imminent flood threats due to unreliability of the information. An irrigation farmer FGD participant expressed dissatisfaction, stating,

> "*Floods frequently occur unexpectedly at night. We typically receive warnings after the damage has already been inflicted, making them useless. Due to the lack of reliable warning information, my crops have been ruined while I am asleep.*"

To mitigate the dissatisfaction, parahydrologists established a two-way communication system among stakeholders involved with the citizen scientists, which included operators of the Legedadi reservoir, EMI forecasters, IWMI researchers, and AAU. They utilized various communication methods, such as phone calls and text messages, to enhance the reliability of warning information.

To ensure that warning information reached diverse at-risk community groups, citizen scientists and residents used informal communication strategies, including mobile phones, door-to-door visits, and word of mouth. Describing this process, a citizen scientist involved in sand mining mentioned how he disseminated the information he received from Legedadi dam operators as:

> *"I work with 60 to 70 sand miners. If I know that water is going to be released from the Legedadi dam, I inform these workers, providing them with an estimated time for when the water will reach our location. Typically, it takes about 12 hours for the water released from Legedadi to reach our area. I also advise them not to enter the river for sand extraction during that time."*

The two-way communication between citizen scientists and relevant parties has also significantly increased the reliability of flood early warning information, thereby cultivating trust among all participants. For example, in the early phases of the CBFEWS implementation, direct interactions between citizen scientists and a Legedadi reservoir operator were established. Nevertheless, difficulties emerged due to a lack of responsiveness from one side. An important occurrence involved a citizen scientist who observed increasing water levels in the Akaki River and sought to contact the Legedadi dam operator to ascertain whether water had been discharged from the dam. The lack of response from the dam operator led to a significant erosion of trust. To address such challenges, citizen scientists suggested the implementation of a system to maintain current contact information for various dam operators, and it was implemented. This is in line with Pocock et al. (2019) who indicate engagement of citizen scientists in EWSs empowers citizens to engage actively in the exchange of information, fostering a balanced interaction. Furthermore, due to the reliability and timeliness of the early warning information provided by CBFEWS, local people have begun to request warning information from citizen scientists. One citizen scientist expressed this by saying:

> *"Other citizen scientists and local people contact me to check if I have received warning information from the Legedadi dam operators or if I have access to meteorology rain forecast data. I am not the only one who contacts local people; they also contact me. If they notice changes in the river, they call me to ask why it is happening."*

Our findings support the studies by Wolff (2021), Pocock et al. (2019), and Gyawali et al. (2021), showing that citizen science and community flood monitoring can boost social capital, improve risk communication, and promote local engagement for equitable warning dissemination.

RESPONSE CAPABILITY

Our results indicate that engaging citizen scientists in the planning and implementation of response plans promotes inclusivity and equity. Testimonials highlight how reliable early warning information empowered people to respond swiftly and efficiently to potential flood risks. This involved measures such as securing agricultural tools and moving people, livestock, and belongings to safe areas upon receiving flood alerts.

A woman living in a flood-prone area highlighted how she benefited from receiving a reliable early warning information from citizen scientists:

> *"While attending my husband's brother's funeral on a Saturday, I entrusted my children to his wife. Concerned about their safety due to water release from Legedadi dam, a citizen scientist called me. I quickly contacted my brother's wife to evacuate my children and secure the house. Thanks to her prompt action, everyone was safe and unharmed."*

BENEFITS AND CHALLENGES FOR ENGAGEMENT OF CITIZEN SCIENTISTS IN THE AKAKI FLOOD EARLY WARNING SYSTEM

The CBFEWS encourages citizen scientists to actively participate in the development and management of the flood EWSs in the Akaki Catchment area. It creates avenues for improved access to reliable information, for sharing insights, for voicing specific needs, for making well-informed decisions, and for fostering trust. It also cultivates a sense of shared ownership and responsibility among participants, enhancing the system's responsiveness at the community level. However, sustainable engagement of citizen scientists in flood EWSs remains a challenge.

Our research indicates that citizen scientists play a significant role in the flood EWSs, driven by several motivational elements, including passion, opportunities for networking, and the acquisition of knowledge. Nonetheless, citizen scientists encounter obstacles such as demands on time, financial constraints, and the requisite effort. One citizen scientist highlighted financial difficulties but expressed that his motivation stems from a desire to help others rather than from financial incentives. This underscores the importance of achieving a balance between the commitment of citizen scientists and the advantages of volunteering.

Our findings also reveal that the lack of legal frameworks and institutional structures at the local level for community-based flood initiatives creates a heavy reliance on personal connections. This burden falls on citizen scientists and hampers long-term sustainability. Furthermore, current policies treat communities as homogeneous, disregarding individual capabilities that affect engagement in EWSs. Lastly, due to resource constraints, engaging only eleven stakeholders limits the diversity of perspectives in decision-making and accessibility to warnings, which is consistent with the findings of Laut et al. (2017) regarding citizen science initiatives.

CONCLUSION AND PRACTICAL IMPLICATIONS

This study explored how integrating citizen science into the flood EWSs in the Akaki catchment area impacts power dynamics. Specifically, it examined the effects on participation, resource distribution, collaboration, and communication among stakeholders to improve system reliability and enhance response capabilities for vulnerable communities. The findings reveal that citizen science played a vital role in addressing power dynamics by allowing collective input in decision-making processes. This enabled active involvement of citizen scientists in meetings, research, and training, gaining better access to information and networks. This empowerment enables them to make informed decisions and reduce reliance on external sources. Additionally, the integration of citizen science encouraged collaboration and dialogue among stakeholders, fostering a sense of ownership, empowerment, and trust within the flood EWSs. Nevertheless, the application of citizen science to address power dynamics within flood EWSs faced challenges, such as insufficient institutional and financial backing and the tendency of policies to view communities as homogeneous groups in terms of their motivation and capabilities.

Our findings have important implications for development policy in the field of citizen science for flood EWSs and for disaster risk management. In environments dominated by a top-down approach, the citizen science model serves to challenge power imbalances by promoting meaningful participation, access to resources, and collaboration with stakeholders. Achieving this requires creating an enabling environment for collaboration and communication between citizen scientists and other stakeholders. Specifically, this requires government support through the development and implementation of inclusive policies, putting in place institutional structures and the allocation of adequate resources. Policies and interventions related to citizen science also need to consider the diverse capacities and motivations.

The relevance of this study goes beyond just flood management. It also adds to the wider conversation on participatory governance, social equity, and community resilience in the face of environmental challenges. It offers valuable knowledge for policymakers, practitioners, and communities who want to improve the ability of at-risk communities to adapt and withstand flooding and other climate-related risks.

DATA ACCESSIBILITY STATEMENT

We provided anonymized data extracts used in this research.

ETHICS AND CONSENT

Informed oral consent was obtained from all participants before being interviewed. This method of obtaining consent was chosen to build trust and strengthen relationships, as individuals tend to feel more comfortable and trusting in verbal communication.

ACKNOWLEDGEMENTS

We extend our heartfelt appreciation to the citizen scientists and community members of the Akaki catchment area as well as key informants from whose active participation and willingness to contribute their time enriched the depth and understanding of our study. We are also grateful to all staff from the Addis Ababa Water and Sewerage Authority, and the Ethiopian Meteorological Institute who participated in this action research.

FUNDING INFORMATION

This action research was supported by the Water Security and Sustainable Development Hub, which is funded by the UK Research and Innovation's Global Challenges Research Fund (GCRF) under grant number ES/S008179/1 from 2019 to 2024.

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

Likimyelesh Nigussie: conceptualization; data curation (lead); formal analysis (lead); methodology (lead); supervision; writing – original draft, review, and editing (lead). Tilaye Worku Bekele: conceptualization; supervision; and writing – review. Alemseged Tamiru Haile: conceptualization; supervision; writing – review and editing. Anna Mdee: formal analysis; methodology; writing –review and editing. Alan Nicol and Charity Osei-Amponsah: formal analysis; writing – review and editing. Joshua Cohen: methodology and writing – review. Hailay Zeray Tedla and Kirubel Demissie – formal analysis and review.

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TO CITE THIS ARTICLE:

Nigussie, L, Bekele, TW, Haile, AT, Mdee, A, Nicol, A, Cohen, J, Osei-Amponsah, C, Tedla, ZH and 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): 9, pp. 1–14. DOI: https://doi.org/10.5334/cstp.763

Submitted: 18 April 2024 **Accepted:** 07 January 2025 **Published:** 04 February 2025