

Distance Matters in Citizen-Based Water Quality Monitoring

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Water pollution remains a critical global challenge, threatening public health and aquatic ecosystems. Governmental efforts to monitor and manage water resources often face limitations due to constrained resources and socio-political priorities that may not prioritize sustainable solutions. Citizen science has emerged as a promising approach, engaging communities in scientific research to expand data collection capabilities and foster environmental stewardship. This paper explores the role of distributed collaboration infrastructure, exemplified by the Water Data Collaborative (WDC), in connecting and enhancing citizen-based water quality monitoring groups across North America. Through participatory design sessions with WDC users, the study identifies essential design features needed to support collaboration and address common challenges such as data standardization and resource sharing. Our findings emphasize the complexity of relationships among citizen science groups, government entities, and higher-order organizations, emphasizing the need for scalable, integrated solutions that avoid creating new silos within the ecosystem. This research contributes insights into how CSCW and HCI can facilitate effective citizen science practices and infrastructure design to advance sustainable water management.

CCS Concepts: • **Human-centered computing** → **Empirical studies in collaborative and social computing**.

Additional Key Words and Phrases: Citizen Science, Sustainable HCI, Distributed Collaboration

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1 Introduction

Water pollution stands as one of the most pressing global threats to public health today. The availability of clean and safe water is not just a necessity but a fundamental human right, yet countless contaminants infiltrate our water supplies, rendering them dangerous for human consumption and devastating for aquatic ecosystems. While government and organizations play a pivotal role in monitoring water resources, they have limited resources and various socio-political motivations often limit discovery and intervention in addressing such environmental catastrophes. The urgency to raise awareness about the origins of water contamination and its severe health implications has never been greater [2, 52].

Citizen science, or community science, emerges as a promising solution to address this crisis by involving community members in scientific research. Citizens typically participate as volunteers and assist professional scientists in various capacities, such as data collection, data analysis, and transcription. This practice, particularly popular in the environmental science domain, significantly enhances the spatial and temporal scope of data collection and processing. Beyond its practical

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benefits, citizen science fosters informal learning, increases community engagement, and empowers individuals to drive change, thus bolstering social capital [5, 14].

In addressing water quality and resource challenges, access to more water data can provide a clearer understanding of how to tackle these issues [9]. In fact, increased citizen science activity has been shown to correlate positively with improved watershed quality [21]. However, the regional nature and field-based attributes of water quality monitoring groups across North America result in some common challenges such as uncertainty about citizen science data quality [12], retention of participants in projects [48], and lack of appropriate technical infrastructure [35]. Water quality monitoring citizen science groups often practice in isolation, and end up reinventing the wheel when it comes to addressing these common challenges. This is because water quality is primarily a regional issue, that citizen science groups often only seek to collaborate locally. This situation becomes worse for smaller grassroots groups because they often have fewer resources and knowledge to address common water quality monitoring challenges and amplify their practices. Previous work [22] has demonstrated the potential of collaborative designs in helping isolated groups discover each other and foster unanticipated collaborations. However, research and design of such distributed collaboration systems remains limited.

This research aims to address this limitation and investigate how infrastructure that supports collaboration between distributed citizen-based water quality monitoring groups can provide a higher-order structure to integrate their practices across North America. In this paper, we present a participatory design study of a collaboration infrastructure designed to connect citizen-based water monitoring groups across North America. We demonstrate how integrating the diverse knowledge, resources, and capabilities of these groups can magnify their efforts and organize their capabilities to support water monitoring practices effectively.

We had previously worked with citizen science water quality monitoring groups. Through these connections, we partnered with a nonprofit organization that was developing a distributed collaboration infrastructure called the Water Data Collaborative (WDC)¹. We used this platform as an example of a distributed collaboration infrastructure design to understand the infrastructure needs of citizen science groups in establishing collaborations and amplifying their practices.

We conducted five participatory design sessions with users of the platform to evaluate its design and elicit recommendations for improving WDC. At the time of these sessions, WDC had recently been launched and was still in its beta version. Due to limited participation and engagement, direct feedback on the design and its features was scarce. To address this, we developed scenarios illustrating the use of each key design feature of WDC. These scenarios provided participants with insights into the platform's capabilities and prompted them to provide comments, views, and feedback.

The primary objective of this study was to understand the following:

- (1) Whether and how a collaborative platform can enable and encourage citizen science groups to establish new regional and national connections.
- (2) Whether and how collaborations facilitated by such an infrastructure can address common challenges faced by the groups.
- (3) What design features are required in a collaborative networked community platform like WDC to effectively support citizen science practices and address the common challenges they face.

This research contributes to CSCW and HCI by providing evidence that a distributed collaboration infrastructure like WDC can enhance discoverability, accessibility, and standardization of water quality monitoring data and practices. The findings highlight the intricate and complex relationships

¹<https://www.waterdatacollaborative.org/>

between citizen science groups, government, and other higher-order organizations in the water quality monitoring ecosystem. The goal is to integrate seamlessly into existing infrastructure without creating more silos or overburdening the ecosystem.

2 Related Work

2.1 Citizen Science and Water Quality Management

Water quality management is a core public service of government. Citizens need to be confident that their local water supplies are adequate and safe. In the United States, for example, the Environmental Protection Agency (EPA) was created in 1970 to coordinate research, monitoring, standard-setting, and enforcement activities. This effort includes a wide range of possible threats and types of pollution, but, in many cases, what is threatened or contaminated is public water.

Monitoring and managing a water system is challenging, but failing to do so is potentially disastrous. For example, public water sources in Cape Town, South Africa, were forecast to be completely depleted by November 2017 due to climatic perturbations in moisture corridors. By late 2018, it appeared that water supplies had recharged, but the longer-term future for Cape Town's water supply is uncertain [6].

Partly in response to such challenges, citizens have started to become more aware and energized about water quality and water quality monitoring. A wide variety of citizen water groups have emerged. These groups make counts for key indicators of water system vitality, such as fish nests and macro-invertebrate insects, measure key parameters, such as pH and stream velocity and volume, gather samples to be tested for various contaminants, and work on mitigation strategies, such as helping to create riparian buffers to increase shade and control erosion near streams. A PNAS study found that citizen participation in water quality monitoring correlates with quality of public water supplies [21, 36].

Citizen science is a category of civic innovation in which volunteers contribute to scientific research projects, and it has been a productive topic for HCI researchers [31]. Citizen science projects can involve a variety of scientific activities, from image classification to audio-recording in the field, and they often involve collecting data from a wide area or a over long period of time [15, 23]. Scientists benefit by distributing the work of data gathering; citizen participants benefit by learning about science—the process of conducting scientific research, relevant scientific terminology [24], and the values that guide such research projects [4, 35]. Recent HCI research has attended to effective strategies for recruiting newcomers to citizen science projects [32] as well as how their participation may develop over time [29].

Depending on the project, participation can look quite different. Some projects rely on participants to collect and contribute data (e.g. air quality, traffic, noise). In one famous example, citizen scientists played an online protein folding game in order to improve a model enzyme [15]. The results of their gameplay produced a scientific innovation culminating in a publication in the journal *Nature*.

More broadly, citizen science projects can typically be classified into three types based on the level of collaboration between volunteers and professionals: (1) *contributory* projects in which volunteers contribute data to scientists (2) *collaborative* projects, where volunteers assist scientists in project design, in addition to data collection (3) *co-created* projects where volunteers and scientists are equally involved in all parts of the project [4].

2.2 Collaboration in Citizen Science

Research in citizen science primarily explores two collaboration types: (1) between volunteers and professional scientists and (2) between volunteers within a citizen science group. The volunteer-scientist relationship is crucial for sustaining citizen science projects, especially since most are

contributory, focusing on data collection rather than deeper collaboration. To foster more collaborative and co-created projects, understanding the motivations and needs of both volunteers and scientists is essential. This approach enhances public participation and project success [16, 40, 43].

HCI research highlights the importance of designing systems that empower volunteers and facilitate interactions with scientists. For example, [37] emphasized providing volunteers with more agency in project design and execution. The development of collaborative platforms, such as the air quality monitoring system [28], showcases how local community involvement can yield significant scientific and social benefits. In terms of volunteer collaboration within citizen science teams, the focus is on creating a sense of community and enhancing informal learning and support for science [19]. Platforms like [33]'s Pathfinder and [50]'s Common Sense Community Site enable volunteers to collaboratively analyze and discuss collected data, fostering public engagement beyond mere data collection.

Popular online citizen science platforms are increasingly utilizing social media features to aid in volunteer recruitment, community engagement, and scientific communication [27]. Platforms like Zooniverse and iNaturalist utilize social media features to facilitate large-scale participation and peer-to-peer collaboration among distributed volunteers and scientists [25, 45]. These platforms challenge traditional top-down approaches by promoting a bottom-up, flexible model of data discussion and knowledge production [26].

Social media platforms also serve as valuable tools for supporting distributed collaboration in field-based projects like water monitoring. These features facilitate interactions and knowledge sharing among geographically dispersed citizen science groups, addressing key issues such as informal learning, volunteer retention, and engagement. Distributed collaboration helps prevent redundant effort by allowing different groups to learn from each other's successes and avoid "reinventing the wheel" [22].

Despite its potential, research on distributed collaboration in citizen science has been limited. Studies have primarily focused on online platforms like Zooniverse and iNaturalist, which support large-scale volunteer engagement across various regions and facilitate peer-to-peer and scientist-volunteer collaborations. HCI and CSCW research has examined the design of these platforms to enhance collaborative efforts [40, 49].

While social networking features in citizen science platforms can facilitate interactions and knowledge exchange, effectively supporting distributed collaboration in citizen science also requires integrated technological infrastructure that addresses challenges related to data sharing, standardization, and analysis. In this paper, we explore how a more comprehensive collaborative infrastructure can enhance the advantages of distributed collaboration in field-based citizen science.

2.3 Distributed Collaboration in CSCW

While distributed collaboration is crucial within citizen science projects, understanding its broader implications and best practices can benefit from insights gained in other fields [46]. Distance makes collaboration amongst teams difficult. There is abundant literature in CSCW and HCI that describes different examples of distributed collaboration. Among these, [38]'s conceptualization of distributed collaboration with respect to common ground, coupling of work, collaboration readiness, collaboration technology readiness, and later added a fifth dimension organizational management [39] is the most well-known framework. More than a decade later, this framework was further evaluated by [3] to corroborate these dimensions of distributed collaboration, and found that common ground, collaboration readiness, and organizational management are still important aspects of distributed collaboration. With the advancement in collaborative technology, collaboration technology readiness and coupling of work are no longer fundamental challenges, at least not in the way Olson and Olson had described in their original article. The conceptualization

of distributed collaboration along the above five dimensions further led [39] to develop the Theory of Remote Scientific Collaboration (TORSC) which aims to identify the factors that are important in determining the success of remote collaboration in science.

The significance of collaboration among distributed scientific communities has grown, especially in addressing global challenges like climate change and healthcare crises. E-science, supported by advanced computational infrastructure, facilitates such collaboration by enabling data sharing, analysis, and experiments among scientists worldwide [18]. In the U.S., the NSF-funded initiative known as “collaboratories” promotes this collaboration, allowing scientists to work together across distances without the need for physical proximity [51]. CSCW plays a crucial role in advancing e-science initiatives through its expertise in distributed technologies and collaboration.

Distributed collaboration in scientific research is a well-established area of study in CSCW and HCI literature. Even though citizen science work practices and infrastructure are different from professional scientific work, lessons and conceptual frameworks from this literature can be helpful in analyzing and articulating distributed collaboration in field-based citizen science.

3 Study Context - Overview of Water Data Collaborative

The Water Data Collaborative (WDC) initially started with the overarching goal of developing technology and other resources to transform and support citizen science initiatives across North America [13]. The goal of WDC is to:

- (1) Promote collaboration between citizen science water monitoring groups across North America.
- (2) Support citizen science groups by providing tools and training.
- (3) Advocate for citizen science data by working with local, state, and federal agencies to help catalog and share best practices and services to see citizen science data in the hands of decision-makers.

They aim to achieve these goals through various tools and resources, including social networks, story maps, and data visualization tools. Some of their main tools include:

- (1) The Mainstem Network
- (2) Virtual Study Design Training
- (3) Story Maps

In this study we primarily used the ‘Mainstem Network’ and the ‘Study Design Training’ as primary tools in the participatory design sessions as the ‘Story Maps’ was still under development at the time of this study. Below we describe the design of the Mainstem Network and Story Maps.

3.1 The Mainstem Network

The Mainstem Network was created by WDC as a national network for community-based water monitoring groups. It is an online network that aims to provide a space for community science groups to connect with each other, form smaller networked communities within the larger network, post and view opportunities, start and participate in discussions, read and post updates in the form of news or posts, and discover new groups. WDC advocates for more community science data to be in the hands of decision-makers. This involves creating resources that can help government agencies discover ways they can support their local community science groups, and raising monitoring standards of community science groups so that their data is usable for decision-makers.

The Water Data Collaborative platform features a homepage with a live feed of user activities and posts, as well as lists of recently active users and recent tweets from the organization’s Twitter account. The platform is organized into several tabs, including *Networks*, where users can join regional networks and connect with others; *Monitoring Programs*, which lists active

projects from various organizations; *Organizations*, which provides a comprehensive list of affiliated organizations; *People*, which allows users to find individual members; *Opportunities*, where users can post or discover job openings, funding opportunities, and more; *News*, which shares updates and articles about the organization's activities; and *Membership*, which outlines membership options and benefits.

3.2 Training Module

The design of the study is a crucial element of every water quality monitoring initiative. It ensures the accuracy and reliability of the collected data, as well as the effectiveness of the methods, equipment, and technologies used in the monitoring programs. "The courses (training module) provided by the WDC aim to support groups in developing and assessing their volunteer monitoring program" [13]. The training is free and anyone can access it and complete it on their own time.

4 Methodology

This study used participatory design methodology and scenario-based design to get user feedback on WDC and elicit design implications and recommendations for further development of WDC. We used the participatory design approach for community informatics as described by [10]. Participatory design is a design paradigm that involves the direct involvement of end-users and other stakeholders in the design process [34]. Participatory design in community-based research involves creating a self-directed and sustainable process of continuous learning. Community-based nonprofits can exert greater control over their limited IT resources by explicitly planning and managing them and by making use of lightweight tools like scenario descriptions of actions and reactions with respect to information technology.

Citizen science plays a crucial role in community-based research as it involves community members, who are non-professionals, voluntarily engaging in data-driven scientific methods to monitor and protect their local water resources. The study aims to evaluate how the design of WDC contributes to successful collaboration outcomes. By involving users and developers of the platform in evaluating and discussing the potential of technology-mediated communication and providing design recommendations, a robust evaluation process is established, facilitating iterative improvements to the platform's design. The participatory design approach signifies a high level of citizen participation, aligning with *partnership* on Arnstein's Ladder [1], where citizens and designers negotiate and share decision-making responsibilities. We suggest a shift in decision-making capacity towards the community, potentially approaching *delegated power*, where citizens hold dominant decision-making authority.

We conducted five participatory design sessions. During these sessions, the platform had a total of 100 members, including both the steering committee members and the first author. Since WDC was in its beta version, the 100 users were recruited by steering committee members through their personal networks within water quality monitoring groups spanning academia, government, and citizen science organizations. Consequently, the majority of platform members hold leadership roles in these groups, ensuring that the study reflects a representative sample of the target community. To ensure a diverse representation of users, we categorized them into two stratas: regular users and steering committee users. From each group, we randomly selected participants and sent them invitations to join the respective design sessions. Each user was invited to participate in only one session, and the assignment of participants to each session was done randomly. All sessions were conducted virtually using the Zoom video conferencing platform. All sessions were audio and video recorded with the consent of the participants. This study was approved by researchers' University IRB. Table 1 provides participant information of all 5 participation design (PD) sessions. Steering

committee members are marked as (SC) in the table. Pseudonyms have been used to ensure the privacy and confidentiality of the participants.

Participatory design sessions usually involve direct participation of the stakeholders in the design process. This “design process” involves not just the wireframing, prototyping, and coding of the system but also other slightly less tangible aspects of design such as requirement elicitation and design ideation [53]. Using this philosophy of design research, we used scenario-based design [8] to depict possible ways different design features of WDC can elicit successful collaboration outcomes. The goal of using scenarios was two-fold: first, it was helpful in prompting discussion and encouraging participants to think about their experiences and also learn about other participants’ experiences; second, scenarios presented concrete narratives of use of WDC which helped elicit specific design recommendations and implications. We presented 1-2 scenarios in each session, depending on the time constraints. Please see Appendix A for the full list of scenarios used in this study.

PD Session	Participant	Organization Title	Location	Affiliation Type
PD1	Ethan	Executive Director	Maine	Non-Government
PD1	Jackson	Director of Water Quality Program	Maine	Non-Government
PD1	Liam	Technical Advisor	Maryland	Government
PD1	Noah (SC)	Executive Director & Cofounder	Pennsylvania	Non-Government
PD1	Mason	Water Stewardship Director	British Columbia, Canada	Government
PD1	Aiden	Senior Director	New Jersey	Non-Government
PD2	Benjamin	Watershed Planner	Michigan	Non-Government
PD2	Mia	Program Manager	Washington	Non-Government
PD2	Harper	Save our Streams Coordinator	Iowa	Non-Government
PD3	James (SC)	Executive Director	Pennsylvania	Non-Government
PD3	Emma	Data Scientist	California	Non-Government
PD3	William (SC)	Program Implementation Coordinator	Washington DC	Non-Government
PD4	Ava	Highschool Science Teacher	Ohio	Non-Government
PD4	Isabella	Executive Director	Pennsylvania	Non-Government
PD4	Michael	Manager of Regulatory and Scientific Affairs	Pennsylvania	Non-Government
PD4	Alexander	Riverkeeper	North Carolina	Non-Government
PD5	Christopher	Research Hydrologist	Pennsylvania	Government
PD5	Sophia	Water Educator Program Coordinator	North Carolina	Government
PD5	Emily	Program Coordinator	Rhode Island	Non-Government
PD5	Olivia	Environmental Program Specialist	Alaska	Non-Government

Table 1. Participatory Design Participant Information

4.1 Data Analysis

Each participatory design session lasted about 1 hour, and each session was audio and video recorded with the consent of the participants. We transcribed all audio recordings before starting data analysis. We used qualitative thematic analysis to analyze the data. Qualitative thematic analysis is a method used in qualitative research to identify, analyze, and report patterns (themes) within the data. It involves systematically organizing and interpreting textual or visual data to identify meaningful themes or patterns that capture the essence of the participants' experiences, perspectives, or responses [7].

We used an inductive and deductive data analysis approach in which we first open coded the data and then, based on the initial goals of the study and the relevant literature, started deductively aggregating similar codes into categories. The first author led the data analysis and periodically discussed the emerging categories with other researchers. These categories again went through the inductive and deductive data analysis approach until we had formed the final themes.

5 Findings

The goal of Water Data Collaborative is to promote both national and regional collaboration, but specifically underscore the importance of national collaboration since that has been a critical limitation of water quality monitoring groups. The participatory research sessions were helpful in getting an in-depth understanding of the goals, practices, challenges, and opportunity for design for citizen-based water quality monitoring groups in their regional and national collaboration endeavors. Since the majority of the groups in this study are located in the United States, "national collaboration" in this context refers to distributed collaboration.

5.1 Goals of Collaboration

Our participatory sessions revealed that regional collaborations are a primary priority for most citizen science groups. While participants acknowledged the potential of national collaborations, their immediate focus remained on addressing regional concerns and ensuring the effectiveness and impact of their daily monitoring activities. Many groups emphasized the importance of maintaining data quality that aligns with local and federal government standards, ensuring that their data is both credible and beneficial for nearby communities. This focus on fostering meaningful local interactions often takes precedence over broader, distributed collaboration efforts. In the quote below, Emily emphasizes that their goal is to find tools that can help them make an impact locally.

"One of the things we're trying to encourage is for our folks not to wait for the government to use our data. Instead, we're focusing on finding tools they can use locally, because that's where real change is going to happen. Here in Rhode Island, our data is actually used for TMDLs and a whole host of other purposes." - Emily, PD5

For some programs, collaboration goals are shaped by their specific mandates. Programs designed for local water monitoring may define distributed collaboration differently from others. For example, Jackson, Director of Water Quality Program in Maine, his program, which initially focused on monitoring and disseminating local lake data for the benefit of the local community, now aims to extend its reach. Their goal is to engage with other professionals, such as research scientists and individuals conducting larger-scale water quality analyses. To achieve this, they seek to create new collaborations and expand their network through a centralized platform that connects various stakeholders, including municipalities, lake stakeholders, and professionals.

Another significant goal for many citizen science groups is achieving recognition for their data by having it accepted into the Water Quality Exchange (WQX). Maintained by the US EPA (Environmental Protection Agency) and USGS (United States Geological Survey), WQX is a standardized

format for exchanging water quality data. Federal agencies use this data for decision-making, research, and regulatory compliance. By adhering to the WQX standard, citizen science groups aim to contribute to a comprehensive, interoperable database that enables more informed decisions related to water resources. For these groups, having their data included in WQX represents a crucial milestone and a validation of their efforts in maintaining high data quality standards.

5.2 Practices of Collaboration

Citizen science groups often prioritize their core tasks, such as data collection, which leaves limited time for collaborative activities with other groups. A critical practice among these groups is maintaining Quality Assurance and Quality Control (QA/QC) for their data. Many groups have adhered to QA/QC protocols for decades to meet government standards, demonstrating a consistent emphasis on delivering high-quality data. For example, Jackson's program focuses on monitoring and disseminating local lake data specifically for the benefit of their local community. However, their approach to data sharing is largely reactive, relying on interested parties to reach out to them rather than actively seeking collaborations.

Our participatory sessions revealed that while distributed collaboration is acknowledged as valuable, it is not the primary goal for most citizen science groups. The absence of dedicated methods or frameworks for building national networks. Some larger organizations, such as the Izaak Walton League of America, have developed their own mechanisms to facilitate collaboration. Through their volunteer science network, they work directly with member organizations to develop monitoring standards and training practices. These collaborations are supported by regular virtual meetings and conferences, connecting watershed groups nationwide and enabling communication and knowledge exchange. For example, the River Network serves as a broader platform for collaboration, bringing together diverse groups through annual conferences and other tools.

For smaller groups with fewer resources, conferences remain the primary means of interacting with organizations outside their region. Events like the "National Water Quality Monitoring Conference" provide opportunities to discuss water quality monitoring efforts and initiatives across regions. Participants acknowledged the importance of such events but began critically reflecting on their collaboration practices only when prompted by specific scenarios during our sessions. For instance, a discussion based on Scenario 2 led one participant to consider how an online platform could complement the traditional conference model, enabling connections with a wider audience beyond localized, in-person events. Virtual platforms offer the potential to bridge geographical distances, making it easier to disseminate information and engage with a broader community.

"So far, conferences have introduced me to many who know about Save our Streams but didn't realize we're active in Iowa too, doing similar work. They just need to connect with our network. Conferences and outreach have been vital for us to make ourselves known in Iowa. A virtual platform might not have the same impact as meeting in person, but it can reach more people, especially on a national scale, bridging distances effectively." - Harper, PD2

Scenarios 2 ("News Feed") and 3 ("Community Science Opportunities") were particularly helpful in evaluating and reflecting on participants' current collaboration practices. These discussions highlighted the benefits of resource-sharing to address gaps in expertise. For instance, many water-focused organizations lack expertise in areas like database design or IT-related tasks. Conversely, IT specialists often do not engage with water-based social networks, creating a disconnect between these skill sets.

"And I have actually seen that happen. So we've talked to our neighboring watershed groups, and one of them just invested in a new CRM tool that we've been using...that is designed for water groups, and so they're feeling like that's really saving them a lot of time and headache and kind of creating something that was more of their own, and maybe not as well-developed like." - Jackson, PD2

Jackson shared a practical example of successful collaboration, where a neighboring watershed group invested in a new Customer Relationship Management (CRM) tool specifically designed for water-focused organizations. This tool significantly reduced complications and saved time, demonstrating how resource-sharing and collaboration can address operational challenges and improve efficiency.

Finally, the collaboration between citizen science water quality monitoring groups and government institutions is pivotal yet intricate. Government agencies rely on citizen science data to address significant monitoring gaps, as approximately 70% of water sources in the United States remain unassessed, as noted by William from PD3. Conversely, citizen science initiatives depend on governmental support to enhance their impact and influence policy effectively. This interdependence underscores the importance of fostering strong, practical collaboration practices between these two entities.

5.3 Challenges of Collaboration

Citizen science groups face substantial challenges in fostering collaboration due to constraints in time, resources, communication, and the diverse expectations of stakeholders. These challenges span multiple dimensions, including government reluctance to utilize data, the absence of centralized platforms, data quality protocols, and resource constraints.

5.3.1 Resource and Time Constraints. A significant challenge for citizen science groups is the lack of time and resources to engage in collaboration beyond their immediate priorities. The demands of daily monitoring tasks often lead groups to de-prioritize distributed collaboration, even when it could enhance their overall impact.

Resource constraints further complicate collaboration efforts, particularly when specialized local expertise is unavailable. Participants highlighted the difficulty of finding knowledgeable resources in specific subject areas, which hampers effective data interpretation and application. Coordinating volunteers and trainers across different regions also becomes a cumbersome task, especially when these individuals are not formally affiliated with organizations that assign monitoring responsibilities.

Additionally, participants reported struggles in finding companions for stream monitoring, underscoring the need for better support networks. Communication limitations exacerbate the issue, as reliance on email often proves inefficient, and alternatives like social media platforms—such as Facebook—raise concerns about privacy and professionalism, hindering widespread adoption.

5.3.2 Government and Citizen Science Collaboration Challenges. Our participatory design sessions highlighted several concerns regarding the collaboration dynamics between citizen science groups and government authorities. These interactions reveal critical challenges, including barriers to data sharing, effective utilization of citizen science data, and shortcomings in communication and support.

One prominent challenge is the reluctance of government agencies to utilize citizen science data, even when these groups adhere to rigorous QA/QC protocols. Agencies ultimately decide whether to adopt the data based on how well it aligns with their objectives, often leaving citizen science groups discouraged despite their commitment to high-quality standards.

“We’ve been doing QA/QC and demonstrating the quality of our data to agencies for decades, yet there’s still reluctance to adopt it. I understand that. Ultimately, whether they choose to use our data depends on how well it aligns with the agency’s objectives. What matters most to me is that our local community finds the information useful and fosters horizontal interaction. We share tools among ourselves, which is beneficial, but finding ways to collaborate effectively with local communities is perhaps even more crucial in some respects.” - Emily, PD5

In another instance, Alexander, a Riverkeeper in North Carolina, shared their experience with the state's Department of Environmental Quality (DEQ). Despite using State-certified labs and approved QAP for grab samples, their organization faced difficulties in getting their data recognized. They identified high levels of fecal contamination in water downstream of concentrated animal feeding operations (CAFOs) and attempted to submit this data to the State for listings to reduce CAFO permits and increase monitoring frequency. However, State authorities initially refused to recognize their data due to a lack of a process for third-party data submission. A lawsuit, "Title Six," eventually mandated that citizen science data meeting the same QAP requirements as DEQ employees and State-certified labs be accepted for listings and permit reviews.

"We've been collecting data for years and trying to use it. Our DEQ, but you know they wouldn't accept it. Um, regardless of what we did, and we finally, we're able actually through a lawsuit to get approval." - Alexander, PD4

This reluctance underscores the pressing need for collaboration at multiple levels. While many groups focus on national-level collaboration, they find that local interactions often yield more immediate and meaningful impact.

Moreover, citizen science groups would benefit significantly from stronger government support in managing and amplifying their programs. Historical support from agencies like the EPA and USDA played a vital role in fostering collaboration and building connections. For example, the EPA provided funding for a volunteer monitoring newsletter and maintained a designated staff member at headquarters to oversee volunteer monitoring efforts. Similarly, the USDA supported facilitation projects that helped strengthen ties between citizen science groups and government agencies.

"We still are working through the Volunteer Monitoring work-group through EPA. But since we're doing it in addition to our jobs, we're not able to do quite as much as we would like to, so we only are able to do a couple of webinars a year, and we have meetings." - Emily, PD5

Emily, Program Coordinator of a group in Rhode Island, explained the significance of historical support their group received from EPA and USDA. The EPA previously provided funding for a volunteer monitoring newsletter and had a designated person at EPA headquarters overseeing volunteer monitoring efforts. Additionally, the USDA offered support through a facilitation project. This support played a crucial role in establishing connections and fostering collaboration between the citizen science monitoring program and these government agencies. However, with the lack of such support, there is additional responsibility and work for citizen science groups, which prohibits them from going the extra mile to improve their programs.

5.3.3 Data Quality, Operability and Management. A significant challenge with data quality is the lack of standardized Quality Assurance Protocols (QAP) and the difficulty of meeting these protocols. Citizen science groups strive to achieve the Quality Assurance (QA) and Quality Control (QC) standards set by government agencies while delivering quality data on time. For instance, many U.S. state agencies require groups to provide qualitative data, such as recording the amount of muddiness during rainfall. However, meeting these standards often proves challenging, leaving groups uncertain about their next steps.

Another key challenge is the difficulty of formatting data to meet the WQX standards. According to Alexander, most organizations use flat spreadsheets to store their data, which are row-based rather than column-based. These spreadsheets, where each row represents a specific time and location, require transposition and additional metadata columns to comply with WQX standards. This process is time-consuming, particularly when working with extensive datasets spanning years, where some metadata, like sensor details or calibration history, may be missing.

Timeliness, credibility, and effective contextualization are also critical for data to be useful in decision-making by government agencies. Data that fails to meet these criteria often becomes a

barrier, rendering it ineffective or disregarded altogether. For example, delays in receiving data during critical situations, such as assessing water licenses during specific ecological events, can make it irrelevant for decision-makers. Additionally, the lack of a framework to interpret the data in alignment with decision-making processes further complicates its use.

Data management issues also pose significant challenges. Christopher, a Research Hydrologist for USGS, highlighted:

"It often comes down to a data management issue...how people store their data, their data storing practices, obviously QA/QC, and stuff like this. It can be incredibly challenging." - Christopher, PD5

These challenges include inconsistent metadata, lack of quality control measures, and data that does not meet specific standards for analysis and integration. Consequently, integrating volunteer-collected data into larger analyses and decision-making processes remains difficult.

A primary frustration for citizen science groups when collaborating with state or federal governments is ineffective communication. Participants expressed their willingness to comply with specific data standards set by regulatory agencies, such as using certain tools or adhering to specific measurement parameters. However, the lack of clear guidelines and expectations from agencies like the EPA creates uncertainty and challenges in meeting those standards effectively. Clear communication about data collection tools and standards is crucial for ensuring that citizen science groups can provide data that meets regulatory requirements.

5.3.4 Collaboration and Stakeholder Alignment. A significant challenge in fostering collaboration is the lack of a comprehensive and centralized platform to bring together diverse stakeholders effectively. This limitation hampers efforts to engage proactively with municipalities, lake stakeholders, and professionals. Jackson, a participant in the study, described the difficulty of involving municipalities due to outdated communication methods like email lists, which feel like "trying to put out 100 little fires."

"But there hasn't really been anywhere out there yet that is a good network that connects municipalities, lake stakeholders, and professionals in an easy manner to alert them to potential issues, and I think that, fundamentally, that is the biggest gap that exists in our interactions with our communities. It has been a challenge because getting municipalities on board with email lists or different things like that is like trying to put out 100 little fires." - Jackson, PD1

Citizen science water quality monitoring groups frequently encounter diverse stakeholder concerns. This diversity leads to the collection of a wide range of data on issues such as transparency, dissolved oxygen, cyanobacteria blooms, and turbidity. Integrating and synthesizing these varied datasets is a complex task that requires effective communication channels and streamlined coordination among stakeholders. However, the absence of a dedicated platform for inter-group communication and the infrequency of meetings further hinder collaboration efficiency.

"And I've tried um through like EPA resources like Maybe there's a listserv, or maybe there's something that there, and there really isn't um. There's not really any way to communicate amongst our group. Um. Aside from like one meeting that happens once a year. If it doesn't get canceled by Covid." - Olivia, PD5

The barriers to collaboration also extend to government agencies' interactions with citizen science groups. These challenges often involve complex coordination efforts to utilize the data effectively. Mason, a Water Stewardship Director from British Columbia, Canada, highlighted the need for substantial investments in technical infrastructure to support quality hydrometric data collection. Multi-partner, multi-government strategies are often required but can themselves become barriers due to the diversity of stakeholders involved.

"Part of it is technical, so the ability to be able to get quality hydrometric data takes investment. So, we, in part, are investing in some infrastructure here within the Okanagan as is the federal government."

So, like many of these strategies it's sort of multi partner multi government that's that can be a barrier."
- Mason, PD1

This highlights the challenges of aligning diverse interests, data collection methodologies, and technical capabilities across various stakeholders. Developing a unified approach to data integration and utilization remains a significant obstacle, further emphasizing the need for platforms and strategies that can bridge these gaps and foster more cohesive collaboration.

5.3.5 Communication and Networking. One significant challenge that emerged from the participatory design sessions was the communication divide between bench scientists and citizen scientists. The challenge lies in effectively integrating the data collected by citizen scientists into larger scientific projects or initiatives. While citizen scientists may contribute valuable data, there can be a disconnect in how this data is perceived and utilized by professional scientists and academic institutions. Isabella emphasizes the importance of bridging this divide by ensuring that both groups recognize and respect each other's expertise and limitations, thereby fostering more meaningful and collaborative outcomes in scientific research.

"Are there questions that agencies could be asking or academics could be asking, based on the type of data that are collected by citizen scientists? So um I think it is a two-way street. It's not just that it has to be high enough quality so the academics can use it. But academics need to realize the limitations citizen scientists and realize that maybe they're just not asking the right question. So it does go both ways." - Isabella, PD4

Conferences currently serve as the primary venue for citizen science groups to meet and network with other groups outside their region. However, these events are not primarily intended to develop collaborations on joint projects. This is because the missions of attending organizations are often geographically different, making alignment on projects challenging. Instead, most groups attend conferences to achieve objectives like gaining feedback on ongoing projects, sharing knowledge and lessons learned, and finding inspiration for new ideas.

"I wouldn't say that I go to conferences with the intent of developing collaborations, like working together on joint projects, because our missions are geographically different often. So those connections are harder to make. But I go there to try to get feedback on things I'm doing, like projects. On a regional level, where we are trying to do the same things, it is more directly collaborative." - Benjamin, PD2

Benjamin, a Watershed Planner for a group in Michigan, explains that the level of collaboration differs depending on the regional context. On a regional level, where organizations work towards similar goals, direct collaborations are more feasible and likely to occur.

5.4 Opportunities for Design Solutions

The fourth participatory design session presented a scenario on data quality, prompting discussion on how the Water Data Collaborative (WDC) or similar collaboration and networking platforms can address challenges related to data quality and assurance. One promising feature of WDC is its "Study Design" training, aimed at improving methodological practices among citizen science groups and enhancing data quality. While participants found the idea of a centralized platform with free study design training beneficial, they emphasized that the training would only be useful if approved by each state's DEP/DEQ or federal agencies like USGS and EPA.

"I think if it falls on DEP's end, you know. Are they satisfied with this training? Do they? People want uh want people to be retrained as they go. And I think if people learn that their data isn't getting used, even if they've gone through this uh study design training, if it's not the DEP protocol to a T that could be disheartening." - Isabella, PD4

Participants also highlighted the importance of data integration and standardization. They emphasized the value of connecting disparate platforms and systems, such as web applications and

databases, through APIs or linking them to standards like WQX. This integration would create a robust, comprehensive system for water quality data, enabling stakeholders to compile reliable datasets for decision-making and collaboration.

In addition, participants noted that current communication methods, such as listservs, are inefficient and time-consuming for sharing alerts and updates with stakeholders. To address this gap, they suggested implementing a centralized network to facilitate timely notifications about emerging water quality issues, such as cyanobacterial blooms, lake closures, or *E. coli* contamination. Such a platform would foster rapid responses and coordination among stakeholders.

“So having a centralized network that could handle some of that, I think, is really important, and a social media style platform could resolve some of that issue.” - Jackson, PD1

Jackson, Director of a Water Quality Program in Maine, explained that a centralized platform could address these communication challenges while also enhancing collaboration among diverse stakeholders. Participants also expressed interest in design features like a map displaying the geographical distribution of water quality monitoring activities, similar to WDC’s Mainstem Network. Such a resource would facilitate collaboration, enabling researchers and organizations to identify and connect with monitoring groups in specific areas.

Additionally, participants expressed interest in design features like a map displaying the geographical distribution of water quality monitoring activities, similar to WDC’s Mainstem Network. Such a resource would facilitate collaboration, enabling researchers and organizations to identify and connect with monitoring groups in specific areas.

“A map that shows the geographical distribution of water quality monitoring activities conducted by various groups... provides an overview of where monitoring is currently taking place.” - Christopher, PD5

The participatory sessions also highlighted the limited user engagement with WDC during the study period, as the platform was still in its initial release phase. Consequently, participants provided limited examples of WDC’s impact. Nevertheless, the discussions offered valuable feedback on current successes, envisioned future use, and design recommendations for improving collaboration and networking.

5.4.1 Current Successful Use of WDC. Despite initial low user engagement in WDC during our study period, some critical successful examples highlight its potential impact in fostering collaboration among citizen science and water stakeholders. WDC can serve as a valuable platform for citizen science groups and environmental professionals to access resources, exchange knowledge, and collaborate effectively.

“The draft framework document we accessed through WDC is helping us ask all the right questions as we redesign our monitoring program. It guides us on who will use the data, our desired outcomes, and provides valuable guidance when we need peer input on critical decisions.” - Aiden, PD1

For instance, in the quote above, Aiden is a Senior Director of a group in New Jersey and got invested in WDC when they found a draft framework document that helped them to redesign their monitoring program. The draft framework document was accessed through the Mainstem Network of WDC. This indicates the value of collaboration and networking within the citizen science community. By leveraging resources from a broader network, the group gains access to valuable guidance and support when they encounter critical questions or challenges.

In addition, when Olivia (PD5) an Environmental Program Specialist in Alaska, first joined the Mainstem Network, they saw a post from someone looking for expertise in collecting metal samples. They encountered difficulties in collecting metal samples in Alaska due to contamination issues. The online platform provided an opportunity to seek advice and solutions from others who may have faced similar challenges or have expertise in addressing such issues.

“And the first post on there is, someone who’s looking for monitoring groups that are collecting metal in their samples. And it’s like Oh, we had all sorts of trouble collecting metal uh here in Alaska because it gets contaminated really easily. So we do actually have some expertise, and I never would talk to that person unless I happen to feel like, you know, commenting right here. Like in a listserv, or I’m never gonna see that unless they posted a follow-up resource somewhere else. Once the question is answered, then That’s it. It’s not publicly available anymore, So I see that as a benefit to something like this.” - Olivia, PD5

Olivia appreciates that the information shared on the online platform remains available to others. Unlike a listserv, where discussions are often limited to subscribers, the platform’s content is accessible to a wider audience. This makes it a valuable resource for sharing knowledge and experiences within the community. The platform facilitates finding relevant expertise, addressing challenges, and accessing publicly available information, creating a more dynamic and accessible space for collaborative discussions and support among monitoring groups and individuals.

5.4.2 Envisioned Use of WDC by the Steering Committee. The steering committee of WDC invested their time, financial resources, and technical expertise in building this platform. It was essential to obtain their feedback and provide them with the opportunity to interact with other users (citizen science stakeholder participants) during the participatory design sessions. Through these sessions, we gained insights into how WDC was envisioned to make a positive impact in the citizen science water monitoring community.

The goal of the steering committee was to facilitate a horizontal (distributed) level of communication, where everyone is on the same level and can freely discuss priorities and share tools. The horizontal communication approach can help build trust between citizen science groups and the government. In the past, there has been a lack of trust between these entities, but the new approach allows for a more cooperative and transparent relationship. They envision WDC to be a platform where stakeholders can openly discuss their needs, capabilities, and available tools. This collaborative platform would allow community groups to share their expertise and resources, fostering a supportive environment for water quality monitoring. While the steering committee acknowledged that this vision of collaboration may take years to fully realize, they remain committed to establishing open communication and trust among stakeholders. Their ultimate goal is to create a sustained and effective platform for community-driven water quality monitoring.

“the current state of community water quality monitoring, there is this inherent vertical hierarchy of, academic data or EPA collected data is the best. But you have community groups who also collect data and they’re the worst, and we may or may not use their data. It’s kind of just cursory to our knowledge, but we want to see more of a horizontal level of communication where community groups feel comfortable talking to folks in the EPA, feel comfortable talking to technical service providers all who are on the same level.” - William, PD3

As explained by William in the quote above, there is an inherent vertical hierarchy in how citizen science data sources are perceived, in that it is sometimes seen as less credible or of lower quality compared to government or academic data. They wish to break down the hierarchical barriers between different data sources and data collectors. They believe that a more inclusive and collaborative approach, where all stakeholders are seen as valuable contributors to the overall knowledge base, would be more beneficial for environmental science and water quality monitoring efforts.

5.4.3 Collaboration Requirements and Design Recommendations. The participatory design sessions yielded valuable recommendations for designing a collaborative platform that supports efficient distributed water monitoring efforts. Participants emphasized engaging stakeholders at different levels of governance—local government, senior government (state-level), and the public—to foster

effective collaboration. They envisioned a platform structured with separate spaces or "boxes" for each level, ensuring tailored communication, data sharing, and collective problem-solving.

"I would draw three boxes, so I would go local Government for sure, which is kind of an operational level, a senior government like the state, and I would say that's kind of more of a policy governance box and the third what box, will be the public." - Mason, PD1

Participants also recognized the importance of addressing different data scales, acknowledging that data requirements vary across situations. The platform should allow for data aggregation to provide a broader context and understanding at a higher level, such as state-level decision-making. At the same time, it should enable detailed, localized data analysis for more specific, localized issues. Providing decision-makers with long-term data sets and tools for meaningful analysis will empower them to make informed choices, especially in projects like building infrastructure or managing water quality.

Moreover, collaboration was also viewed as a vital educational tool, enabling citizen science groups and schools to share knowledge and foster environmental stewardship among students. This inclusive approach would not only enhance data collection efforts but also promote public understanding of environmental impacts and the importance of local engagement.

"If we can get data from the upstream and downstream of us to see how biomagnification bio accumulation... So everything we do upstream, because we're further north, makes a difference downstream. So if I can get that through their heads and help them to take care of this environment that is theirs." - Ava, PD4

Furthermore, the design recommendations emphasized creating an intuitive and user-friendly interface to encourage active engagement and facilitate both active and passive connections among stakeholders. While active connections often occur through in-person meetings and organic networking, a digital platform could potentially reach more people across the nation, expanding the network's reach and impact. Participants envisioned the platform as a central hub or database connecting practitioners and volunteers nationwide, enabling the exchange of ideas, methodologies, and best practices in water monitoring.

"So I definitely think that if this platform had sort of the foothold it could fill that need for us creating... for different regions that have a lot of SOS volunteers. And then within that, you could have conversations just like a normal social media feed... But I think it's an important tool as long as you have the right number of users." - Harper, PD2

The participatory design sessions also highlighted several challenges and considerations that need to be addressed for successful collaboration between distributed citizen science groups. One critical consideration that emerged is the need for standardizing study designs and methodologies. Participants stressed the importance of methodological consistency across different groups to ensure comparable data quality and enhance collaboration efficiency. Additionally, ensuring the platform's usability across varying levels of technical expertise was highlighted as essential for broad participation and sustained engagement. An intuitive interface that simplifies access to tools and resources was identified as crucial, particularly to accommodate busy professionals and educators.

"I think the biggest thing is just kind of like there needs to be a standardized process of if there's a bunch of different people doing the same measurement or doing the same thing, it needs to have a process that's done the same way, so that the data can be compared." - Michael, PD4

6 Discussion

This study presents a participatory design user study conducted with the Water Data Collaborative (WDC) Platform to explore how collaborative platforms can facilitate and encourage citizen science groups to establish new regional and national connections.

The research involved five participatory design sessions with platform users and steering committee members. Participants were presented with scenarios depicting how different design features of the platform could facilitate collaborations and the associated benefits. The findings shed light on current collaboration practices and challenges among citizen science groups, as well as between citizen science groups and government agencies. Moreover, the study provided insights into how WDC currently supports collaboration practices and addresses challenges, along with feedback and design recommendations to enhance specific aspects of the platform's design.

Based on the key findings, it is evident that WDC is a unique initiative and serves as a good example of an infrastructure, connecting distributed citizen science groups and improving water quality practices and the health of water resources. However, it is crucial that the collaboration design remains customizable to enable groups to foster and address regional collaboration issues while also providing accessible ways to discover and establish more distributed and national connections.

To achieve this, it is vital for WDC to avoid creating additional silos and instead integrate with existing successful national networks. Additionally, adopting data and methodological standardization practices approved by the government will be instrumental in enhancing the platform's effectiveness. Table 2 summarizes the key collaboration challenges identified by this study and the potential of WDC in addressing these challenges with its current design.

6.1 Distance Matters in Citizen-Based Water Quality Monitoring: Design Implications for Distributed Collaboration in Field-based Citizen Science

The Water Data Collaborative (WDC) marked the initial stride towards establishing a networked community of distributed citizen science groups within the realm of water quality monitoring. Nevertheless, the user study conducted on WDC illuminated a range of complex challenges encompassing practices, collaboration hurdles, and organizational objectives. Olson et al. [39] conceptualized distributed collaboration across five dimensions: common ground, collaboration readiness, collaboration technology readiness, coupling of work, and organizational management. This framework, serving as a valuable analytical tool, has been successfully applied as a perspective to scrutinize collaboration practices across diverse landscapes, including the design of laboratories [20] aimed at fostering effective collaboration among dispersed scientific teams, and more recently effects of organizational distance in industry research teams [47]. Thus, we employ this framework to dissect the design implications for achieving effective distributed collaboration within citizen-based water quality monitoring groups.

6.1.1 Common Ground. Common ground, rooted in shared knowledge, refers to mutual awareness among collaborators that each party possesses the same understanding [11]. Developing common ground is critical in distributed collaboration, where miscommunication, unevenly distributed information, and differences in access speed often lead to a lack of mutual understanding [17].

Our findings reveal significant challenges in establishing common ground within citizen science data practices. Ineffective communication between citizen science groups and higher-order organizations, such as academic institutions and government agencies, hampers adherence to data quality assurance protocols and under-utilizes the data collected by citizen groups. Government entities often reject data due to coordination challenges and quality verification issues, highlighting a deficiency in mutual understanding.

Previous research underscores the bidirectional relationship between citizen science and policy, demonstrating how governmental policies can either facilitate or hinder citizen science and how citizen science can contribute to policymaking [30, 41]. Addressing these challenges requires standardized protocols for study design, data quality control, and assurance. Beyond data quality,

Challenges	WDC’s Potential Role in Addressing Challenges
Resource and Time Constraints - Lack of time to prioritize collaboration. - Difficulty finding specialized expertise and coordinating volunteers. - Inefficient communication methods (e.g., reliance on email, privacy concerns with social media).	- WDC can serve as a centralized communication platform to streamline coordination and reduce reliance on inefficient methods like email. - WDC’s networking features can connect volunteers and experts across regions, providing better support for resource gaps.
Government-Citizen Science Collaboration - Reluctance of government to utilize citizen science data. - Lack of historical support (e.g., funding, facilitation projects).	- WDC can provide agency-approved training and tools (e.g., "Study Design" training) to align citizen science efforts with government standards. - WDC’s horizontal communication model can foster trust and transparency between citizen science groups and government agencies.
Data Quality and Management - Difficulty adhering to QA/QC standards. - Formatting issues for WQX standards. - Ineffective communication of data requirements. - Lack of clear frameworks for data submission and integration.	- WDC can standardize QA/QC protocols and offer training to ensure compliance with government standards. - WDC can integrate tools for data formatting, metadata management, and submission frameworks to streamline the process.
Collaboration and Stakeholder Alignment - No centralized platform for diverse stakeholder engagement. - Challenges with integrating and synthesizing varied datasets. - Barriers in aligning methodologies and technical capabilities.	- WDC can act as a centralized hub for stakeholder engagement, offering modular spaces tailored for local, state, and public collaboration. - WDC’s data integration tools (e.g., geographical maps and APIs) can bridge gaps in data synthesis and visualization.
Communication and Networking - Disconnect between citizen scientists and professionals. - Limited opportunities for collaborative project development. - Lack of sustained engagement mechanisms.	- WDC can facilitate continuous engagement through a digital hub connecting citizen scientists and professionals nationwide. - WDC’s platform can support project sharing, feedback mechanisms, and long-term data aggregation for collaborative initiatives.

Table 2. WDC’s Potential Role in Addressing Collaboration Challenges

citizen groups’ local ties and knowledge should be leveraged to address specific water quality issues and secure grant funding for improvements.

6.1.2 Collaboration Readiness. Collaboration readiness refers to the preparedness of individuals or groups to engage in distributed collaboration, influenced by organizational structure, incentives, diversity, and heterogeneity [3]. While national collaboration was a secondary goal for most citizen science groups, smaller organizations prioritized regional efforts due to resource and time constraints. These groups often focus on core activities such as regional data collection and dissemination, while larger organizations with more resources expand their networks nationally.

Missed opportunities for collaboration are common, as the work of smaller groups often remains invisible to neighboring groups and the broader community [9, 22]. The WDC seeks to address these gaps by establishing a national network that enhances visibility, breaks regional barriers, and fosters connections among citizen science groups. Although the findings highlight the complexity of achieving collaboration readiness, unexpected benefits of information sharing across a national network suggest the potential value of dedicated collaboration infrastructure.

6.1.3 Collaboration Technology Readiness. Collaboration technology readiness refers to the ease with which members of the groups adapt and adopt to collaboration technologies [38]. Collaboration technology readiness was an important factor for distributed collaboration in the 1980's because collaboration technologies were still nascent and organizations did not have experience with using these technologies [3]. Given the advancement and proliferation of collaboration technologies, this aspect of distributed collaboration is no longer pertinent.

The PD sessions helped us understand that groups were comfortable using the Water Data Collaborative. However, there were instances where participants perceived the Water Data Collaborative as just another platform they would have to learn to use. They did not desire a new platform to seek connections, as this was not their primary goal. With the exception of a few participants who were excited about the prospect of distributed collaboration, most people had their own methods for finding resources and were resistant to change. Nevertheless, achieving distributed collaboration is a worthwhile goal. While we agree that we may not necessarily need another platform, there are alternative ways to incorporate the concept of the Water Data Collaborative. For instance, a widget that integrates seamlessly into existing platforms used by these groups.

6.1.4 Coupling of Work. Coupling of work refers to the characteristics of collaborations, such as inter-dependencies between groups and collaboration practices.

We gained insight into the coupling of work in distributed collaboration practices. Regional collaborations are of greater importance, aligning with different goals and types of collaborations. For example, collaboration with regional or state governments provides essential support and resources, allowing their data to inform government decision-making. Additionally, disseminating information and making water quality data accessible to the public serves the purpose of keeping the public informed.

To address these diverse coupling challenges, the Water Data Collaborative (WDC) aims to support collaboration at different levels. The platform will offer customized spaces for local government, senior government, and the public. These separate spaces will ensure that relevant information reaches the appropriate stakeholders and encourages focused discussions within each group. This approach acknowledges the importance of addressing different data scales: enabling data aggregation for a broader context and understanding at higher levels while allowing detailed, localized data analysis for specific issues.

6.1.5 Organizational Management. Organizational management refers to the practices within an organization that impact distributed collaboration. These practices encompass various aspects, including organizational structure, legal considerations, and managerial issues, all of which can significantly influence distributed collaboration.

In the context of citizen science, organizational management plays a crucial role in shaping collaboration in two distinct ways. Firstly, the size of the organization, as discussed previously in the context of work coupling, has a substantial effect. Smaller organizations tend to prioritize regional collaborations, while larger organizations engage in both regional and national collaborations.

Secondly, organizational management in citizen science involves horizontal and vertical collaboration. Horizontal collaboration refers to interactions between different groups, whereas vertical collaboration pertains to the relationship between volunteers and project leaders. This research focuses on supporting horizontal collaborations within distributed collaboration and the design of the WDC. While emphasizing horizontal collaborations is vital, it's essential not to overlook the relationships and connections among group volunteers. Volunteers play a central role in these groups as they are responsible for data production. Consequently, collaboration platforms like the WDC should incorporate additional layers into their collaborative structure and provide mechanisms for volunteers to participate in this collaborative ecosystem actively.

6.2 Implications for CSCW and HCI

The challenges and opportunities identified in this study can be examined through the lens of articulation work and process [42, 44]. Articulation work involves the specific tasks of fitting together various components of a project to ensure a smooth workflow. Within citizen science, this could involve standardizing data collection methods, coordinating volunteer efforts, and aligning with government standards. The articulation process encompasses a broader set of actions beyond specific tasks, aiming to bring together and maintain all the interlocking elements of the project. In citizen science, this process could involve building relationships, negotiating roles and responsibilities, and addressing challenges. WDC provided a concrete example of the articulation process in action. The WDC embodies the articulation process by fostering relationships, facilitating communication, standardizing practices, and addressing challenges to effectively integrate citizen science efforts into the broader water quality monitoring ecosystem. However, challenges identified in this paper pave way to discuss further design implications and recommendations for improving citizen science practices in HCI and CSCW.

Addressing these challenges requires leveraging the principles of articulation work to streamline processes and support distributed collaboration. For instance, smaller citizen science groups often face significant resource limitations, which impact their ability to engage in both regional and national collaborations. These challenges are further exacerbated by inefficient communication methods. Participants in the study perceived the WDC as potentially reinventing the wheel, risking becoming just another national network that creates silos instead of breaking them. This paradox highlights a significant design challenge for CSCW and HCI: achieving distributed collaboration without overwhelming the ecosystem with additional digital systems. To address these issues, streamlined communication tools should be developed that integrate seamlessly with existing platforms commonly used by these groups. For example, instead of introducing entirely new platforms, widgets or extensions can enhance the functionality of familiar tools like listservs. Additionally, offering automated scheduling and notification features tailored to the specific timelines of regional and national citizen science projects can help volunteers manage their time effectively and ensure coordinated data collection efforts.

A core aspect of the articulation process is the alignment of data collection practices with government standards, ensuring that citizen science data is credible and actionable. Interactive training modules designed to simulate real-world data submission processes can support this alignment. These modules would familiarize participants with expectations, such as meeting WQX standards, while real-time feedback systems in data platforms could help identify and rectify data

quality issues before submission. These features embody articulation work by directly addressing the friction points in integrating citizen science outputs into government workflows.

The articulation process also involves managing relationships between diverse stakeholders with varying expertise, technological resources, and motivations. Collaborative platforms must offer tailored spaces for stakeholder groups such as local governments, researchers, and volunteers. These spaces should not only facilitate targeted communication but also incorporate data visualization tools, such as geographical maps and APIs, to synthesize complex datasets into accessible formats. By bridging gaps in knowledge and communication, these tools enable stakeholders to align their goals and methodologies effectively.

Volunteers play a central role in citizen science projects, making their engagement a critical element of articulation work. Platforms should empower volunteers by incorporating mechanisms that demonstrate the tangible impact of their contributions on project outcomes. Peer-to-peer mentoring features can further support the articulation process by fostering a network of shared expertise and learning within the community. By creating avenues for volunteers to actively participate beyond data collection, these mechanisms reinforce their role in the broader collaborative ecosystem.

Finally, the broader articulation process demands an infrastructure that not only integrates disparate elements but also evolves to address systemic challenges like siloed operations. By embedding articulation work as a design principle, citizen science platforms like WDC can transform from static data repositories into dynamic systems that support the coordination of tasks, interdependencies, and diverse perspectives. This requires prioritizing transparent communication channels, standardized data practices, and tools that facilitate scalable, sustainable collaboration.

6.3 Limitations and Future Work

This research investigated how the design of distributed collaboration infrastructure can help connect isolated citizen-based water quality monitoring groups, enabling them to share data, knowledge, and resources. However, we acknowledge some limitations of this research that future work should address with more comprehensive study and platform design.

First, the Water Data Collaborative represents an initial stride toward developing a distributed collaboration infrastructure that can effectively address monitoring practice and collaboration challenges. It does not epitomize the ideal infrastructure. At the time of this study, the platform was in its beta version, with all features not yet released and limited users and engagement. Hence, it was difficult to demonstrate how such a platform could support distributed collaboration. Future work should focus on longitudinal studies to understand the true affordance of such a platform.

Second, our collaboration goals and participants did not include citizen volunteers to voice their opinions on how such a platform could affect their volunteer monitoring work. Future research in this area would benefit from a more comprehensive user study including all stakeholders and studying the effect of collaboration design for all.

Third, the qualitative nature of our research limited the evaluation of the WDC platform. Although our data provide evidence of the positive effects of distributed collaboration, the evaluation is not balanced and cannot be quantified. Future research could benefit from a more comprehensive mixed-methods evaluation.

7 Conclusion

This study presents a participatory design user study conducted with the Water Data Collaborative (WDC) Platform to explore how collaborative platforms can facilitate regional and national connections for citizen science groups. The study also aimed to identify essential design features for such platforms to support citizen science practices and address common challenges.

The research involved five participatory design sessions with platform users, focusing on scenarios depicting how different design features could facilitate collaborations and their benefits. The findings highlight current collaboration practices and challenges among citizen science groups and between these groups and government agencies. Additionally, the study provided insights into how WDC currently supports collaboration practices and offered feedback and design recommendations to enhance the platform.

WDC has the potential to connect distributed citizen science groups and improve water quality practices. However, the platform's design must be customizable to address regional collaboration issues while enabling the discovery of national connections. It is crucial to avoid creating additional silos and integrate with existing national networks. Adopting standardized data and methodological practices approved by the government will also enhance the platform's effectiveness. Below we summarize the key design solutions that evolved from this research:

- (1) **Streamlined Communication Tools:** Develop widgets or extensions to integrate with existing platforms like listservs and create tailored spaces for diverse stakeholder groups to enhance communication.
- (2) **Data Quality Alignment:** Implement interactive training modules and real-time feedback systems to ensure data quality and alignment with government standards.
- (3) **Enhanced Task Management:** Incorporate dynamic task reallocation features and dashboards to track progress, address bottlenecks, and maintain project momentum.
- (4) **Data Visualization:** Use tools like maps and APIs to present complex datasets in accessible formats, fostering shared understanding and collaboration.
- (5) **Volunteer Empowerment:** Provide feedback mechanisms to showcase volunteer contributions and introduce peer-to-peer mentoring to support knowledge sharing and engagement.
- (6) **Scalable Infrastructure:** Design transparent, standardized, and scalable platforms that avoid silos and support diverse inter-dependencies.

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A Scenarios

A.1 Citizen Science Networks (data collaboration)

AB citizen science group monitors water quality in the Chesapeake Bay area. One of their biggest monitoring challenges has been managing their data. They want a central data repository where they can upload and access their data. They join the Mainstem Network to find a solution to their data management problem. While browsing the existing networks, they come across the Chesapeake Bay Cooperative and discover that this is a network for all the Chesapeake Bay community science groups. They join the network to connect with other groups in their area and find out that the Chesapeake Bay cooperative has a data explorer, which is a tool for storing and sharing data collected by all the community.

A.2 News Feed (social networking)

Prof. Jane Doe is a water scientist at the State University. She joined the Mainstem Network to learn more about citizen science initiatives in the field of water quality monitoring. She comes

across an article on his news feed by a local citizen science group. The article summarizes a recent macroinvertebrate study completed by the group. Prof. Doe is very impressed with their work and comments positive remarks on their post. The group sends a personal message to Prof. Doe, to potentially collaborate on a monitoring project.

A.3 Citizen Science Opportunities

Stream watchers monitoring group have their own database that requires maintenance and upkeep. They need to hire a technology specialist to maintain and update their database. They post this job opportunity on Mainstem Network's Opportunity tab and also ask for recommendations on network forums. They get leads for this position and hire a technology specialist on a contract.

A.4 Wiki Resources (informal learning)

The senior citizen science group is a water quality monitoring group composed of older adults who periodically collect data on stream quality. They primarily collect data on paper and then manually type it into a Google spreadsheet. Hence, despite following strict monitoring and quality control protocols, the manual data collection approach is tedious and often leads to human errors. They join the water data collaborative to network and share news about their monitoring activities. Through this network and collaboration they discover a wiki of monitoring resources and find open access data collection and monitoring tools that they were not aware of before. They consult their network for recommendations and advice, and download a water quality data collection app that directly uploads data to a central data repository.

A.5 Study Design for WQM (Data Quality)

Creek Watchers is a water quality monitoring group in New York. The group was formed by concerned citizens of the York Creek watershed to monitor local water quality and drive evidence-based action in the community. However, for the last 10 years this data has only been used to display reports from the monitoring activity on the group's website. The group has been unsuccessful in submitting their reports to the New York DEP because they are not able to meet the required quality control and assurance standards. When the Creek Watchers join the Mainstem Network, they see a post on their news feed about WDC's study design training module. Intrigued and interested by this post, they follow the link and join the study design training module. The training illuminates the current flaws in their monitoring process and ways they can improve the data quality control and assurance practices.

A.6 Forum Discussions (information/knowledge exchange)

XY monitoring group is a newly established community science group in Virginia. They join the water data collaborative and Mainstem Network to learn and network from other citizen science groups. Since the COVID-19 pandemic, they have been struggling to recruit and train volunteers. The group joins the Chesapeake Monitoring Cooperative network and posts questions about recruiting and training volunteers during the pandemic on the forum page. They get responses from some well-established monitoring groups in this network who share their new virtual recruitment and training model for water quality monitoring.

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