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Citizens and stakeholders' engagement for monitoring and awareness of hydrological cycle

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Tesi di dottorato di:
Dott. Andrea Spasiano

Coordinatore del corso

Prof. Alessandro Sorrentino

Firma ………

Tutore

Prof. Alessio M. Braccini

Firma ………

Co-tutore

Prof. Salvatore Grimaldi

Firma……………….

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1. Introduction

Hydrology is the discipline that studies the distribution, movement, and processes related to the water cycle as well as the chemistry and biology of water resources (Chow Ven et al., 1988; Brutsaert, 2005; Davie & Quinn, 2019). It is composed of multiple fields of study, according to the different aspects and phases of the water cycle and the different characteristics of water resources: from precipitation to the morphological characteristics of watercourses, from the study of surface water to groundwater, and the biological and chemical composition that determines the quality of water resources (Chow Ven et al., 1988; Brutsaert, 2005; Davie & Quinn, 2019).

Knowledge of hydrological processes and water characteristics is essential for water resources management (WRM) and its social, economic, and cultural uses (Chow Ven et al., 1988). Hydrology and WRM relies on the availability of data at large geographic and temporal scales (Assumpção et al., 2018; Zheng et al., 2018). The acquisition of consistent, up-to-date, spatially distributed data is, therefore, one of the fundamental aspects of studying phenomena and processes related to the cycle and use of water resources.

Traditional tools for data acquisition in hydrological and environmental research are remote sensors, flow meters, and rain gauges. New analytical developments for hydrology include the use of remote sensors and satellite technologies, and infrared cameras.

Despite the advanced level of environmental monitoring technologies, data scarcity represents one of the main issues in the implementation of water management models and the study of environmental and landscape phenomena (Lisjak et al., 2017; Sy et al., 2019). Data scarcity implies not only lack of information but also temporal frequency, velocity and geospatial coverage (Lisjak et al., 2017). This issue is crucial in the context of rural and remote areas, where rain gauge stations and remote sensing monitoring technologies are few (Fienen & Lowry, 2012).

Such solutions, however, often present difficulties related to economic costs and susceptibility to risk factors, as well as the fact that they do not guarantee uniform coverage across the territory. New data collection techniques based on crowdsourcing and citizen engagement are increasingly being used to address issues related to hydrology, environmental monitoring, earth observation, urban planning, and resource management (Le Coz et al., 2016; Perdana & Ostermann, 2018; Kankanamge et al., 2019). Participatory techniques and approaches to data collection offer relatively low-cost solutions for increasing spatial and temporal data coverage or providing benchmark values.

In this context, digital transformation offers new opportunities to broaden participation in scientific research and earth observation from physical communities to virtual communities based on internet-based technologies (Basco-Carrera et al. 2017; Braccini et al., 2018) and Information and Communication Technologies (ICT) supporting crowdsourcing activities (Hossain & Kauranen, 2015; Modaresnezhad et al., 2020). The use of ICT thus implies not only the adoption of digital technologies (smartphone, personal devices or PCs), such as data collection and analysis tools. ICT indicates a broader system given by the set of processes, activities, software and data to generate new knowledge, products or services (Majchrzak et al., 2016). The use of ICT involves actors with specific goals and values, not just generic users (Majchrzak et al, 2016).

Digital transformation is intended as a disruptive and broader process that supports or changes organizations' strategies and values' propositions (Vial, 2019; Wessel et al., 2021) or create new organizational identities (Wessel et al., 2021). In the context of environmental monitoring and earth observation, it poses several challenges from different perspectives:

- Technological level: design and development of digital technologies and platforms suitable for data collection, data validation and volunteers' engagement (Skarlatidou et al., 2019).
- Organizational level: implementation of strategies aimed to the recruitment, participation and coordination of people within groups or communities; the diversification and coordination of tasks; co-creation of information (Newman et al., 2012; Liberatore et al., 2018).

- Socio-cultural level: behavioral and mindset change, environmental awareness and openness to change (Jennet & Cox, 2018; Sharma et al., 2019; Palacin et al., 2021).

The use of participatory approaches implies multidisciplinary research perspectives, aimed at the integration of knowledge, methodologies, and tools. In the field of environmental monitoring, scientific research issues are thus offered from a holistic perspective, aimed at integrating methods and tools of environmental, social and organizational sciences with the support provided by digital technologies and Information and Communication Technologies (ICT).

Participatory approaches constitute a new organizational model to support collective actions aimed at sustainability and environmental awareness (Basco-Carrera et al. 2017; Braccini et al., 2018). In particular, the role of scientific research, in this sense, is to identify functional models and procedures for public participation in support of strategic decisions and the production of new forms of knowledge, linked to open science (Hall et al., 2022).

New research paradigms are emerging to identify and investigate on intersection and interlinkages between hydrology, social sciences, and other academic disciplines in addressing water issues (Nardi et al., 2022; Hall et al., 2022). Examples in this sense come from socio-hydrology as discipline that investigate on relational mechanisms between human-water systems underlying the management of processes related to water, land and urban systems (Sivapalan et al., 2012; Wesselink et al., 2017; Pande & Sivapalan, 2017).

The application of participatory approaches does not reflect predefined paradigms and procedures. Rather, they derive from the contexts of application and from the purposes set in the design phase. Participatory approaches often derived from empirical first- hand experiences.

In this context, citizen science is establishing as a new paradigm of participatory approach to scientific research, towards solutions to participatory and concerted research issues. The application of citizen science offers to the hydrologists and water management scientists new research skills for implementing analytical models through the integration of traditional data collection methods with information provided by volunteer citizens, using their own personal mobile devices (Lisjak et al., 2017; Assumpção et al., 2018; Weeser at al., 2018; Win et al., 2019). The advantage offered by personal mobile devices is the ability to offer a continuous flow of data, constantly updated and with widespread geospatial coverage, at low cost (Buytaert et al., 2014; Mazzoleni et al., 2017). Data methods collection and citizen engagement are often entrusted to the development of digital platforms, in which voluntary users collect and send information under the supervision of institutions and experts (Newman et al., 2011). Citizens' engagement in scientific research and knowledge production activities, however, can present strong risks linked to socio-cultural factors such as personal perceptions, human behavior of the volunteers, motivations and interests at the base of participation and validity of social engagement methods (Meek et al., 2016; Leibovici et al., 2017).

Citizen participation and engagement in scientific research and production processes varies according to the roles and tasks assigned to volunteers. In a nutshell, three levels of participation can be distinguished: (1) collaboration, (2) dialogue and (3) concertation (Bonney et al., 2009; Phillips et al., 2019). In the first case, the activity of citizens is limited to the collection and submission of data. In the second case, the level of involvement extends to the analysis and interpretation of data. In the third case, the citizen is involved in all phases of the research, including the definition of the research design and the dissemination of the results (Bonney et al., 2009; Phillips et al., 2019). These distinctions will be taken up and deepened in the next chapters of this thesis. Specifically, in Chapter 2, definitions of citizen science will be presented, and possible ideal types will be outlined. In Chapter 3, these ideal types will be proposed as possible models for setting up online citizen engagement activities.

Haklay (2013) proposes a similar model of theoretical schematization of citizen engagement in scientific reasearch on four levels:

1. **Crowdsourcing:** volunteers as data collectors
2. **Distributed intelligence:** volunteers as data interpreters
3. **Participatory science:** volunteers' participation in problem definition and data collection

4. **Extreme citizen science:** volunteers' collaboration in problem and data collection.

The schematization proposed by Haklay (2013) is an adaptation of participatory approaches in the context of geographic citizen science. Geographic citizen science constitutes a peculiar category where the collection of localized information is an essential component of scientific monitoring and co-production activities. In this context, citizens act as sensors on the ground with the support of tools such as global positioning systems (GPS) and geographic information systems (GIS) by releasing volunteered geographic information (VGI) (Goodchild, 2007). Haklay's scheme projects citizen science in the context of cyberscience and online interactions.

Online citizen science offers new perspectives for the access, participation and scientific interaction between citizens and expert researchers (Aristeidou et al., 2017; Aristeidou et al., 2021). The online extension of participatory research activities, supported by internet-based technologies, have advantages in terms of: (1) broadening of participation (Cappa et al., 2016; Laut et al., 2017); (2) widespread and capillary data collection (Aristeidou et al., 2017; Aristeidou et al., 2021); (3) collaboration facilitated by overcoming physical, social, and geographic barriers (Cappa et al., 2016; Laut et al., 2017); (4) investigation of motivational aspects and behavioral patterns underlying voluntary participation (Aristeidou et al., 2017; Aristeidou et al., 2021). Web-based or mobile technologies also promote communication and formalize the learning and teaching of tasks and skills for volunteers (Aristeidou et al., 2017; Aristeidou et al., 2021).

This thesis deals with the issue of citizen science as an innovative approach to scientific research that sees the participation and engagement of non-experts in the planning, conceptualization, and implementation phases. Participatory approaches have long been studied and taken into consideration to innovate organizational models, implement and increase the availability of low-cost data, instill awareness and knowledge, evaluate the cultural and socio-economic impacts of scientific research, make citizens and stakeholders aware and participate in decision-making and research processes through organizational models based on collaboration, dialogue, and consultation.

This PhD research work offers an investigation into citizen science as an innovative approach to scientific research in the field of environmental and hydrogeological monitoring in terms of environmental sustainability and public awareness. Environmental and social sustainability current issues, an integral part of European and national programs that guide policies and decision making in environmental matters and land use planning. Participatory approaches to scientific research include the scope of expanding the availability of data useful for environmental monitoring, supported by public awareness and knowledge of the effects of environmental monitoring on a social and economic level. Given the current need for public engagement in environmental monitoring, according to organizational and decision-making models based on collaboration and participation, the main open questions – and debated in the academic and decision-making fields – concern the participatory methods, long-term engagement and the validation of unofficial data deriving from the direct observation of citizens, often not experts in environmental and territorial issues.

1.2 Citizen science in the environmental policies and in strategic scientific guidelines

This section addresses the relevance of citizen science in the debate around strategic policy making and European academic research guidelines in the pursuit of environmental, social and economic sustainability goals. Specifically, this section investigates the connections between citizen science and the framework defined by the 2030 Agenda and the Sustainable Development Goals (SDGs) and the European Union Green Deal.

1.2.1 Connection between citizen science and SDGs

In 2015, the United Nations General Assembly adopted the document Agenda 2030 for Sustainable Development. The document is an action program through which UN member countries developed 17 Sustainable Development Goals (SDGs) to be pursued by 2030 (Figure 1.1). These goals are broken down into 169 targets.

Figure 1.1. Table of Sustainable Development Goals (source: United Nations).

The SDGs contribute to environmental and social sustainability by incentivizing strategic actions and measures on local and global scales aimed at the management and security of environmental resources, equitable access to resources, and the maintenance of natural and urban ecosystems. Among the most critical aspects in the pursuit of the SDGs at the local level are the adoption of suitable indicators and the availability of data for monitoring and verification activities. Official statistical data are the primary source for monitoring progress toward the SGDs at the local level (Ballerini & Bergh, 2021; Sprinks et al., 2021). However, official data are not always and consistently available and updated, highlighting gaps at the geographic level. The 2015 resolution recognizes the use of informal data through forms of public/private collaboration and citizen engagement. This possibility has been reiterated repeatedly by official UN reports and documents that cite citizen science as a solution to address data scarcity and the definition of suitable and inclusive indicators (United Nations, 2018). In particular, the integration of citizen science and data from the private sector into monitoring systems was recognized in the synthesis report on SDG6 Clean Water and Sanitation (United Nation, 2018; Quinlivan et al., 2020). Recently, several studies have focused on investigating the effective contribution of citizen science data through exploratory case studies (Ballerini & Bergh, 2021; Biraghi et al., 2022) or surveys to measure the impacts of citizen science in the pursuit of the SDGs (Fritz et al., 2019; Fraisl et al., 2020; de Sherbinin et al., 2021, Sprinks et al., 2021), providing operational guidelines.

According to a Stockholm Environmental Institute study (West & Pateman, 2017) the contribution that citizen science can provide as a methodological approach in the measurement and pursuit of the SDGs is articulated in the following terms:

- **Contributory citizen science:** Enlarging citizen participation in monitoring with the support of crowdsourcing techniques for data collection.
- **Collaborative citizen science:** Involving citizens in defining national/local targets to measure SDGs.
- **Co-created citizen science:** implementation of policy and research.

The relevance of citizen science in academic debate and policy implementation on environmental and social sustainability has been reflected in initiatives within the European Union such as the Citizen Science SDGs Conference in Berlin in October 2020. The conference was an opportunity for discussion on citizen science as an approach to address current challenges and direct European policies in the context provided by Agenda 2030 with the involvement of research institutions, policy makers, stakeholders, civil society organizations and citizens.

Despite the importance of the topic, however, some studies point to the marginal space that citizen science occupies in SDGs monitoring processes and methodologies. This is particularly due to: (1) lack of unambiguous criteria and procedures for measuring data quality; (2) different ways of collecting and sharing data; and (3) absence of citizen science in the legal framework and organizational schemes (Fritz et al., 2019; Fraisl et al., 2020). This is also compounded by the lack of adequate infrastructure for data collection and sharing (Moczek et al., 2021). These studies identify the development of exploratory case studies as the main solution to the critical issues raised, with the aim of establishing standards and best practices that can be replicated on larger scales and in different contexts (Fritz et al., 2019; Fraisl et al., 2020).

1.2.2 Citizen science in the EU context: Green Deal and the Italian PNR 2021-2027

Citizen science is also a recurring issue within the European Union. In recent years, citizen engagement has assumed a strategic role in the implementation of scientific activities and policy making. In 2016, a report by the Joint Research Centre (JRC) posed significant thoughts and recommendations on the subject (Figueiredo Nascimento et al., 2016). Citizen engagement is part of the European Commission's strategies for transparent governance, citizen-institutional relations, understanding of social concerns and feedback on policies. JRC document outlines recommendations to make citizen engagement effective and structural through a change in institutional culture, communication, coordination between local projects and initiatives, and development of pilot case studies. In this context, citizen science is seen as an iterative process of collaboration between citizens and experts that includes data collection, analysis and co-creation of knowledge. Citizen science initiatives can raise understanding of social needs and requirements, identifying scientifically sound solutions and generating new ideas to support policies and service development.

The JRC's commitment is to promote citizen science as a component of public participation in policies in Europe, starting with initiatives based on research and the scientific method (Schade et al., 2017; Manzoni et al., 2019). Research should consider the socioeconomic impacts of policies, their effectiveness and public understanding through citizen engagement in hands-on activities (Schade et al., 2017). In this aspect, the JRC has organized initiatives and events aimed at deepening the topic of citizen science, to discuss points inherent in technological aspects to support volunteer activities; institutional for building networks around environmental protection agencies and civil society organizations; application of citizen science on different geographical scales (Manzoni et al., 2019). The latter points are associated with the use of digital technologies for broader engagement.

However, understanding socioeconomic impacts and outcomes remains an open question, as does the evaluation of citizen science impacts in environmental policies (Bio Innovation Service 2018; Turbé et al., 2019). Especially, citizen science projects are mainly focused on environmental monitoring versus resource management and efficient use (Bio Innovation Service, 2018). However, three main benefits of citizen science are recognized: (1) policy relevance, through the identification of problems, evaluation of solutions, and policy formulation; (2) scientific excellence, providing scientific evidence on which to base decisions; (3) citizen engagement, including diverse perspectives to focus research and policy making on real needs and empower people to draw attention to local issues and propose solutions (Figure 1.2) (Bio Innovation Service, 2018; European Commission, 2020).

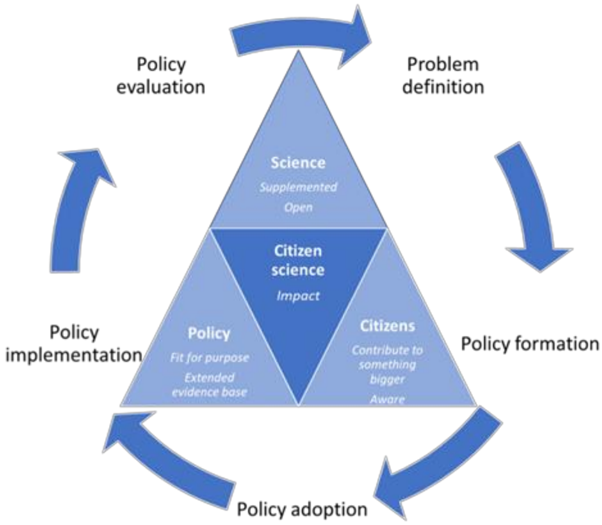


Figure 1.2. Three main pillars of citizen science in the policy cycle: scientific excellence, citizen engagement and policy relevance (source: European Union, 2020).

To date, however, the presence of citizen science in national-level institutional strategies still appears limited (Manzoni et al., 2021). Moreover, citizen science activities scattered across the European Union follow strategies closely linked to the local context, each with its own unique characteristics (Manzoni et al., 2021). The work of groups of experts and researchers in the EU is to define common strategies and procedures, building on inventories of initiatives and best practices (Bio Innovation Service, 2018; Turbé et al., 2019; European Commission, 2020). The common feature is the central role assumed by EPAs in conducting and coordinating activities set on citizen science (Rubio-Iglesias et al., 2020). The adoption of the Green Deal provides a new impetus to the debate and application of citizen science in Europe. Unveiled in 2019, the Green Deal sets out strategies to address climate and environment-related challenges. The purpose of the Green Deal is to conserve and strengthen natural capital and social well-being from the impacts of environmental hazards. Research and innovation occupy a central role in implementing strategies in the context of the Green Deal. New scientific research approaches, set on intersection between disciplines and citizen engagement, are prioritized to identify innovative solutions to achieve the goals of the Green Deal (Hadjichambis, 2022). Research activities should combine societal pull and technological push within the funding framework provided by Horizon Europe.

Within the broad EU research programs, numerous projects address citizen science from different disciplinary purposes and perspectives. Since 2011, funded projects on the topic of citizen science have seen a significant increase, especially within Horizon 2020/Horizon Europe, where co-production and co-creation are pillar topics (Figure 1.3). Under Horizon 2020, funded projects have mainly focused on strengthening the excellence and creativity of scientific research in support of policy, mobility, training, and innovation (78). Significant numbers were also recorded in projects related to *Societal Challenges* (62), on climate action, environment and resources efficiency or on food security, sustainable agriculture, water research and bioeconomy; and in projects related to *Science with and for Society* (52). Other projects focused on *Industrial Leadership for the development of industrial technology solutions*.

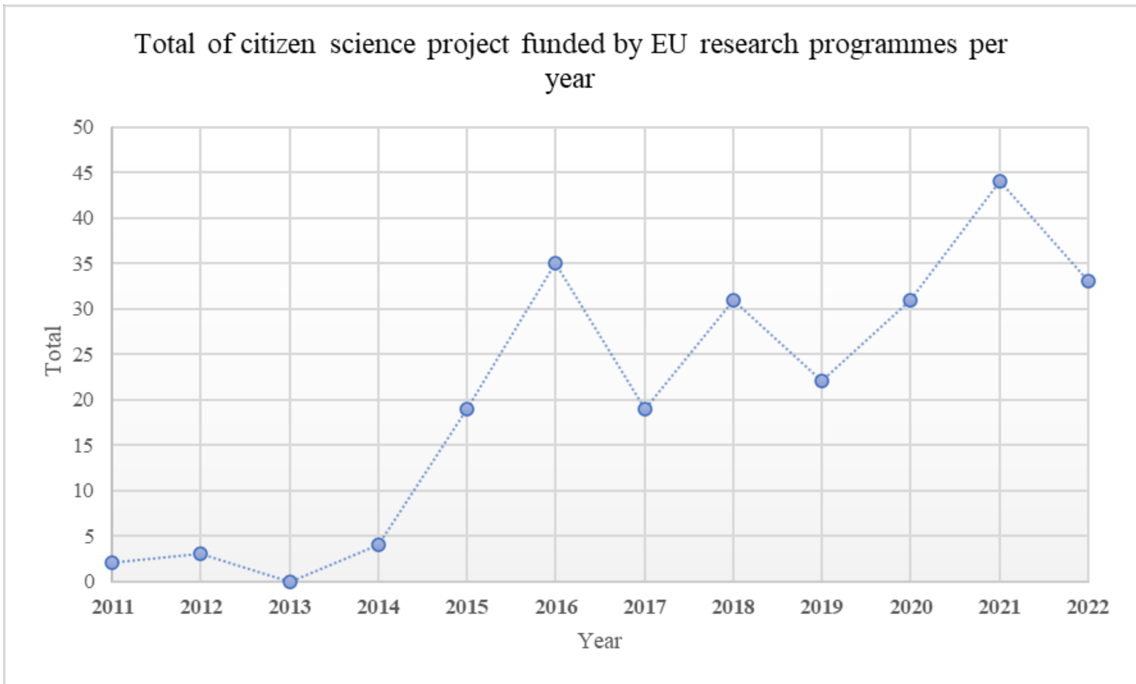


Figure 1.3. Total of citizen science projects funded by EU research program per year.

Under the current Horizon funding program, most citizen science projects find application in H.1.2 Marie Sklodowska Curie actions aimed at encouraging young people's careers in scientific research (10); in H.2.2 on culture, creativity and social inclusiveness (10); in H2.6 on the topic of food security, bioeconomy, natural resources, agriculture and environment (10). Other projects focus on developing digital technologies and solutions for health (4) and widening participation in science and innovation (4).

The research guidelines defined in the European context are also implemented in Italy, where citizen science is fully included in the National Research Program (PNR in Italian acronym) 2021-2027. The PNR is the document that guides research policies in Italy, identifying priorities, objectives, and actions. The PNR includes specific initiatives to promote citizen science to bring research closer to citizens in a common path characterized by sustainability. According to this vision, scientific research must be oriented toward identifying real solutions and needs expressed by citizens. The involvement of citizens and stakeholders serves to enrich scientific research with ideas, anticipating changes and innovations. Citizen science finds its place in *Security for Social and Natural Systems*, a research theme that includes the disaster risks reduction and impacts of natural and man-made disasters. The PNR recognizes the essential role of citizens in risk prevention and governance activities.

1.3 Methodology and structure of the research

1.3.1 Research gap and questions

As evidenced by research programs and guidelines in European environmental policy, citizen science is a topic of great scientific and academic relevance towards solutions to current problems.

However, many gaps are still evident in the adoption of citizen science as a methodological approach to empirical research. First, a precise and universally agreed definition of citizen science is still lacking (Eitzel et al., 2017). To date, citizen science appears to be still an experimental research method, based on multiplicity of early-stage case studies conducted with procedures and methods strongly related to the local context or specific research objectives (European Commission, 2019; European Commission, 2020). This aspect implies a further gap regarding the absence of predefined procedures for setting up replicable participatory research initiatives, obstructing the possibility of comparative studies. Common procedures for collecting and validating data and observations provided by citizens are lacking. The development of case studies is still an essential research method to identify common procedures that can be replicated in different contexts (Fritz et al., 2019; Fraisl et al., 2020). Second, citizen science studies focus mainly on data collection for environmental monitoring and conservation. However, few studies investigate the socioeconomic impacts and potential benefits in terms of sustainable use and resource efficiency. Furthermore, a few studies investigate participants' motivations and performance, which are useful in explaining the mechanisms underlying engagement. Based on these considerations, the following research questions are formulated:

- **RQ1:** What essential characteristics distinguish citizen science?
- **RQ2:** What insights can be grasped for integrating citizen science in organization and management of volunteers?
- **RQ3:** How can citizen science (crowdsourcing and participatory approaches) support the advancement of hydrological and socio-environmental sciences?

The research work was limited to addressing only a few aspects related to the gaps that emerged. First, the research was directed toward establishing predefined procedures for studying hydrological change by investigating the performance of volunteers. Second, the research aimed to investigate the motivations behind volunteer engagement and test recruitment techniques to initiate citizen scientist communities in the initial stages of monitoring activities. Finally, the research work focused on the design and development of ad hoc digital solutions to incentivize hydrological change monitoring with citizen engagement.

The research questions first aim to define a transdisciplinary theoretical framework to support early-stage citizen science projects on hydrological monitoring. Second, the research questions aim to test the theoretical framework on empirical contexts.

Citizen engagement is a strategic objective for a broader, continuous monitoring to develop increasingly reliable and in-depth models in the prevention, communication and awareness of hydrogeological risks. The advantages relating to risk prevention and mitigation derive from continuous monitoring activities implemented from a technical and technological perspective.

Participatory approaches to scientific research involve basic citizen awareness. Data collection is a significant but partial part of testing citizen science approaches. Implementation of citizen science projects also involves systematic communication strategies aimed at instilling awareness and coordinating the actions of individual volunteers within an organized and structured group.

Starting from these assumptions, the research project aims to investigate citizen science approaches to test long-term engagement strategies of volunteers in environmental monitoring and scientific research. Particular attention will be addressed to the recruitment and engagement methods of volunteers and the ability to provide reliable data and observations through the support of digital tools. This research aims to explore the potential of digital technologies in raising awareness and knowledge and online community building for long-term strategies in citizen science projects. A particular aspect of this research concerns the problem of starting a community of citizen scientists from first-hand experience.

1.3.2 Research design

To answer the research questions the research design is structured as following steps:

1. Meta-literature review on Citizen science topic.
2. Definition of procedures to support first-hand citizen science activities.
3. Design and development of exploratory case studies to test citizen science principles in real context.
4. Results interpretation.

The meta-literature review is a particular systematic review limited to analyze articles to highlight concepts, methodologies and tools that distinguish citizen science as a scientific research approach. It represents the basis for the research, aimed at building the theoretical framework for applying citizen science principles in empirical case studies. The objective of this item was to define guidelines to initiate early-stage citizen science case-studies. The outcomes of this phase are reported in Chapter 2 of this thesis. The meta-literature review activity took place in March-December 2020 during the first year of the doctoral program. The chapter has been published as review paper for the *Special Issue MDPI Sustainability*, entitled *The involvement of crowds for advancing knowledge, promoting innovation and nurturing new entrepreneurial ventures*.

The second phase of the research focused on the design of methodological procedures for implementing data collection through volunteers training and communication campaigns. This phase was preparatory to the initiation and implementation of exploratory case studies. In this phase, methodological procedures were developed to implement data collection, facilitate the training and engagement of volunteers through face-to-face training activities and communication campaigns with the support of web-based solutions. The purpose of this phase was to define volunteer engagement recruitment strategies through communication and training campaigns supported by web-based technologies and platforms. The outcomes of this phase are reported in Chapter 3. This chapter has been presented at the XVIII Conference of the Italian Chapter of Association Information Systems (AIS) 2021 *Digital resilience and sustainability:*

people, organizations, and society which took place at the University of Trento from 15 to 16 October 2021. The contribution has been included in the session *Participation, engagement, and coproduction for social innovation in turbulent times*. The session focused on the correlation between the participation of citizens in the processes of scientific production and the development of collaborative initiatives between citizens and institutions with a view to sustainable development supported using digital solutions and ICT as collaborative tools. This contribution fits into the context of doctoral research by shedding light on the technological aspects underlying citizen science in the context of digital transformation, having clarified theoretical concepts and methods that helped define the theoretical framework. Chapter 3 has been published as a conference paper in the volume *Exploring digital resilience. Challenges for people and organizations*, part of the Springer Lecture Notes in Information Systems and Organisation series, Vol. 57, Cuel R. et al., Springer International Publishing. ISSN: 2195-4968. The grant is available from August 14th, 2022.

The third phase focused on the development of empirical research activity. In this regard, two case studies were selected to (1) test methods and controlled data collection procedures addressing the lack of data in the monitoring of hydrological processes and in the management of water resources; (2) experimenting online recruitment activities and develop engagement strategies through trial-and-error learning process; (3) understand the limitations and issues of starting citizen science communities; (4) design applications to support engagement in future research developments. The selected case studies are part of ongoing academic work by researchers from the University of Tuscia and Water Resources Research and Documentation Center (WARREDOC)-University for Foreigners of Perugia on hydrogeological monitoring and prevention of environmental risks.

The fourth and final phase focused on developing comparative methods for analyzing and validating observations, testing citizens' ability to provide valid data by comparing observations with official or expert data. Both quantitative and qualitative methods were considered to investigate volunteers' performance. Quantitative methods were used to compare citizen science data with comparison values provided by experts or official data, which were useful for establishing margins of error. Qualitative methods were employed for contextual insights into volunteers' performance.

Mixed methods were performed to verify the effectiveness of voluntary observations, the ability of users to provide performing data for the purpose of co-producing scientific knowledge and assessing the levels of knowledge and awareness of citizens on issues of environmental interest. The analysis of the results according to mixed methods will serve to evaluate changes within the citizen scientist community to set up new bottom-up engagement models aimed at promoting participatory production and environmental governance processes.

Chapter 4 and 5 constitute the empirical part of the research. Chapter 4 reports results from first case-study, testing the principles of citizen science outlined in the literature review work. First case study principles of citizen science were applied for the engagement of citizens in the estimation of water levels to obtain benchmark values useful for the monitoring of small ungauged basins with ephemeral characteristics. Citizens were invited to examine a series of continuous images to evaluate water level variation during a rainfall event. The first case study has been published as research paper in the Research Topic *Innovative Sensing, Observing, Measuring and Analyzing Human-Water Data* of the journal *Frontiers in Water*. The contribution is the result of empirical research resulting from the results of the first phase of theoretical research presented at the 1st Sociohydrology Delft (Netherlands) Conference in September 2021.

Chapter 5 is a draft work that describes the initial stages of second case-study. In this case study, citizen science principles are employed to test the citizen's ability to detect rainfall intensity through direct observation. The purpose of the study is to develop methods and solutions set on citizen science to expand rainfall data collection methods by integrating them with official rain gauges. Citizens were invited to qualitatively estimate rainfall intensity through direct observation. The case study was conducted between November 2022 and January 2023.

Table 1.1 summarizes papers that compose this thesis work related to each stage of research design.

Paper number	Reference	Research design phase
1	Spasiano, A., Grimaldi, S., Braccini, A. M., & Nardi, F. (2021). Towards a transdisciplinary theoretical framework of citizen science: results from a meta-review analysis. *Sustainability*, *13*(14), 7904.	1)Meta-literature review on Citizen science topic
2	Spasiano, A., Nardi, F., Grimaldi, S., & Braccini, A. M. (2022). Engagement of Online Communities Within a Citizen Science Framework for Improving Innovative Participation Models: Insights from Hydrology and Environmental Monitoring. In *Exploring Digital Resilience: Challenges for People and Organizations* (pp. 41-54). Cham: Springer International Publishing.	2) Definition of procedures to support first-hand citizen science activities.
3	Spasiano, A., Grimaldi, S., Nardi, F., Noto, S., & Braccini, A. M. Testing the theoretical principles of citizen science in monitoring stream water levels through photo-trap frames. *Frontiers in Water*, *5*, 4.	3) Design and development of exploratory case studies to testing citizen science principles in real context.
		4) Results interpretation.
4	POP-Rain: citizen observations of spatial rainfall intensity (Draft version)	3) Design and development of exploratory case studies to test citizen science principles in real context.
		4) Results interpretation.

Table 1.1. List of papers that compose thesis' structure.

Part I: Theoretical framework

2. Towards a transdisciplinary theoretical framework of citizen science: results from a meta-review analysis

2.1 Introduction

Citizen science is a set of science-driven methodological approaches that engage citizens and the general public in scientific research activities (Bonney et al., 2009; Buytaert et al., 2014; Jordan et al., 2015; Bonney et al., 2016; Voinov et al., 2016). Citizen science programs are generally transdisciplinary, allowing multiple disciplines to join efforts with citizens and stakeholders to solve societal challenges cross-fertilizing various areas of scientific research (Newman et al., 2011; Knapp et al., 2019).

Advances in digital, web-based and mobile technologies recently brought new stimuli and opportunities linked to data collection and analysis that lie on volunteers' participation (Buytaert et al., 2014; Ferster et al., 2013; Lahoz & Schneider, 2014; Grainger, 2017; Skarlatidou et al., 2019). It is well recognized, the scaling potential of digital and web-based technologies to enlarge the communities' and volunteers' participation, making easier the collection and analysis of data from citizens' contribution, by reducing cost of data collection (Frigerio et al., 2018) and guarantying large spatio-temporal coverage (Buytaert et al., 2014). In this perspective, online interactions through social media platforms can enhance public participation within the theoretical framework of online communities as new potential actors of citizen science approaches. Volunteered users' interactions may contribute to create large database, address the lack of information and support large-scale surveys and interviews (Heiss & Matthes 2017; Zheng et al., 2018).

Citizen science is a research approach derived from ecological, environmental and earth observation sciences (Peter et al., 2019). Hydrology, water resources management and land use/ urban planning represents major fields of application of citizen science (Buytaert et al., 2014; Nardi et al., 2022) to address data scarcity and build innovative analytical models. The integration of computer science – which investigates into technical issues—and social science (Heiss & Matthes, 2017; Kythreotis et al., 2019) – is going to broaden citizen science investigation on motivational aspects, human behavior and socio-economic implications (Nardi et al., 2022). In this way, citizen science is not just an auxiliary methodology, but is going to become a cross-cutting discipline (Buytaert et al., 2014) with characteristics of a distinct field of inquiry (Jordan et al., 2015).

From an experimental approach to sectoral scientific research, citizen science is gradually evolving towards large-scale application models, aimed at integrating methods and tools from different disciplines. This evolution involves not only conceptual and epistemological changes, but also the organizational level. The latter concern aspects such as the engagement of volunteers and the stakeholder within organized communities to support scientific activities, the assignment of roles and tasks within voluntary organizations, and the extension of research goals towards cognitive, behavioral and organizational issues.

Despite the recent and rapidly increasing heterogeneous and vast set of citizen science applications, a theoretical framework is still missing. Application of citizen science in the transdisciplinary field seems to reflect empirical or experimental investigation approaches, limited to specific research areas, rather than being based on established theoretical models. Scientific efforts oriented towards the definition of the theoretical framework of citizen science are found in addressing hydrological challenges (Nardi et al., 2022). The Citizens AND HYdrology (CANDHY) Working Group – established by the International Association of Hydrological Sciences (IAHS) – is engaged in conceptualizing a transdisciplinary framework for valuing citizen science in hydrological science by promoting joint efforts with computer and social sciences. CANDHY's joint efforts aim at integrating the human and behavioral mechanism into its framework (Nardi et al., 2022).

The need to combine the social and technological into citizen science approaches offers new insights for modelling processes in scientific research and for investigating organizational changes in participatory approaches. However, these aspects are not systematized within a replicable and universally applicable theoretical framework.

The lack of a transdisciplinary theoretical framework constitutes a research gap in the topic of citizen science. In order to reduce this gap, this work aims to review concepts, tools, organizational and engagement issues, limits and opportunities deriving from multi-disciplinary application of citizen science. This contribution takes origin, therefore, from the need to provide theoretical insights for building and managing citizen science projects, that can be applied for designing a new and replicable participative approach. Research questions, at the base of this work, are: What essential characteristics distinguish citizen science? What insights can be grasped to define a theoretical framework applicable at the transdisciplinary level?

To reach this goal, this chapter illustrates the findings of a systematic meta-review consisting of an accurate selection and revision of journal review articles in order to summarize the most recurrent concepts, methods, research design approaches and tools related to citizen science.

Chapter 2 is structured as follows: Section 2.2 introduces the adopted research design in the literature meta-review analysis, by presenting work methodologies and its results. Section 2.3 illustrates findings of meta-review analysis divided in general definitions and common issues on citizen science practices; volunteers' recruitment and engagement; tools and data; outcomes in terms of socio-economic benefits; limits and challenges. Section 2.4 is focused on discussion in which describing the significance of findings.

2.2 Research Design

The research design is based on a reasoned selection of journal review articles on citizen science topics aimed to extract concepts, definitions, methods and tools from different disciplines, such as environmental studies, water resources management and land use and resources management. In particular, journal review article selection aims to investigate aspects related to human behavior, volunteers' recruitment and engagement by the use of information systems and digital technologies in order to enhance the role of online communities into citizen science approaches.

Research questions, at the base of this work, pose reflections on specific concerns such as: (1) level of engagement from data collection activities to research design and final outcomes dissemination; (2) impacts on organizational and management issues with the support of digital and web-based technology – such as, personal (geolocated) devices, social media, apps; (3)

socio-economic benefits based on people's awareness and knowledge around common concerns.

Focusing attention to these three specific concerns, a research query was first defined into the database index, following a Title–Abstract–Keywords selection. Two indexing databases were selected for this purpose: SCOPUS and Web of Science. In the latter case, the query was carried on through Topic selection, the equivalent of the Title–Abstract– Keywords selection on SCOPUS. Considering the vast number of scientific publications on the topic, authors set work as a meta-review analysis, by selecting and analyzing only review articles in order to point out common definitions, concepts, methods and technologies that characterize citizen science approaches over the disciplinary boundaries.

As illustrated in Table 2.1, this query considered "citizen science" as the pivotal key- words, related to a selected group of keywords concerning participatory approaches, information systems, organization studies and computer science through the Boolean operator AND. Then, authors applied a filter, including only review journal articles.

Item	Description
Source	SCOPUS database—Web of Science
Query	TOPIC ("citizen science" AND ("participatory approaches" OR "participative approaches" OR "crowdsourcing" OR "public engagement" OR "public participation" OR "community-based monitoring" OR "participatory monitoring" OR "peer production" OR "online communities" OR "digital technologies" OR "social media" OR "human behavior" OR "motivation" OR "recruitment" OR "volunteers" OR "decision-making" OR "citizen surveillance" OR "information systems")) Refined by LANGUAGE: English and limited to DOCUMENT TYPE: Review journal paper
Results	233 documents results
Papers retained after: - No abstracts records elimination Repetitive results	164 documents results
Paper retained after: Title and abstract selection	68 retained documents 42 uncertain results 54 excluded

Table 2.1. Selection steps of review journal articles.

Query, firstly, provided 233 results by adding results from both databases. Then, the work proceeded with a data extraction method to organize results into an Excel database. Here, results with no authors and/or abstract were eliminated. Then, the work proceeded to eliminate repetitive and redundant records, because of their presence in both database sources. Finally, a protocol of criteria was adopted for the selection of review articles. Criteria selection was structured in: (1) title and abstract selection and (2) full-text selection. In the first point, authors only selected results with the term "citizen science" among title, keywords and abstract. In fact, some results refer only to participatory approaches and, in any case, are limited to crowdsourcing or crowdfunding or aimed to support no scientific purposes. In the second point, the analysis gave priority to articles that investigate on recruitment and engagement issue, such as motivation, human behavior, data collection and accuracy validation protocols, tools and technologies used for citizen science purposes. In this step, biases such as there being no review article or book chapter were excluded. In any case, some results were classified as review although they present specific cases study. Finally, the protocol excluded articles in which citizen science is not the paper's topic, but just mentioned as one of innovative scientific approaches, among others. Results obtained confirm the multidisciplinary and transdisciplinary characteristics of citizen science. Multidisciplinary means that the application of citizen science covers several subject areas, that range from agriculture to hydrological sciences and water resources management to involve social sciences and humanities, as illustrated in the pie chart in Figure 2.1.

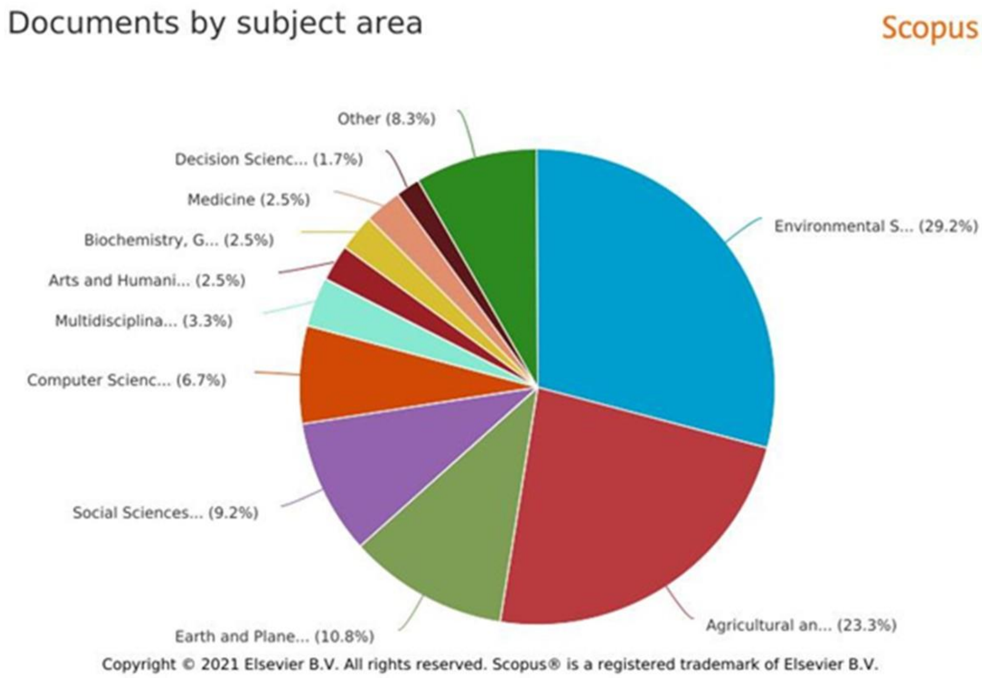


Figure 2.1. Documents by source based on 70 selected results (source: Scopus).

Although these multidisciplinary characteristic, environmental, agricultural and earth observation sciences are the most common topics that adopt citizen science approaches, a minority of publications refer to social sciences and computer sciences, as illustrated in the graph in Figure 2.1. Social sciences investigate behavioral and motivational aspects at the base of community building (both physical and online). Social science also investigates into the cultural, jurisdictional and economic background in order to contextualize the citizen science environment of application for supporting qualitative research. While computer sciences are focused on finding technical solutions for citizen science projects, such as the use of social media, development of web platforms and user-friendly interfaces, supporting the quantitative analysis of data collection, with the integration of statistical methods. The residual percentages attest to a growing interest in citizen science towards disciplines in which the experimentation of participatory models is usually limited or null.

Transdisciplinary means that citizen science approaches integrate different scientific backgrounds and research design for science-driven solution-oriented applications to solve a specific problem that requires support and engagement of a wide range of potential non expert users and actors (e.g., stakeholders, industries, public agencies, general public, etc.) that are interested or impacted by the issue of interest (Nardi et al., 2022). For example, conservation studies or participative environmental and water resources management projects often require sociological skills to understand volunteers' behaviors within an organization. Similarly, citizen science approaches require skills in organization studies to understand the functioning of volunteer groups and the assignment of roles and tasks within an organizational structure as well as IT skills for the development and implementation of suitable tools for participants' engagement, data collection and analysis activities. The selection procedure adopted brought to light conceptual, epistemological, technological and organizational issues related to the application of citizen science in empirical research contexts. The structure of findings in the next section was organized to report these aspects in detail, highlighting frequent opportunities and limitations in the application of citizen science.

2.3 Findings

2.3.1 An Overview on Definition of Citizen Science

Citizen science refers to the participation of the general public (non-experts) in the generation of new scientific knowledge (Nardi et al., 2022; Dickinson et al., 2012; Welvaert et al., 2016; Larson et al., 2020) and in facing data scarcity, gathering meaningful information and addressing the lack of systematic coverage of extended or complex domains (Zheng et al., 2018; Peter et al., 2019; Lawson et al., 2015). Non-expert participants' engagement is functional to challenge new environmental and scientific issues through a capillary monitoring usually insufficient if limited to experts (Brammer et al., 2016), and to build new knowledge (Lee et al., 2020) based on a new collaborative and shared research design between expert scientists and citizens that implies a common determination of scope, scale and activities, such as research question definition, data collection and analysis methods, outcomes discussion and dissemination (Newman et al., 2011).

Citizen science constitutes an innovative research approach aimed at the integration of human and societal perspectives into scientific tasks (Adler et al., 2020). Humans have a pivot role in the construction and definition of new research design, in the two-fold scope to: (1) investigate into bidirectional relationships between environmental and socio-economic systems (Adler et al., 2020); (2) model new organizational processes supported by flexible interaction between human and computer (Voinov et al., 2016; Van de Gevel et al., 2020).

Citizen science offers new possibilities to develop science through bidirectional trade- offs of information and knowledge between scientists, experts, stakeholders and volunteers in general or the public (Ryan et al., 2018). Scientists can connect volunteers' contribution and information to broader scientific literature. At the same time, contributors can guide scientists in data interpretation and discover common concerns to which science can give answers and solutions though a constant bottom-up observation of phenomena under investigation (Ryan et al., 2018). In this view, citizen science is a tool that coordinates citizens to action (Groulx et al., 2017), combining scientific purposes with decision and policy-making processes under a community-based approach (Adler et al., 2020; Commodore et al., 2017), also if it means including subjective element into scientific tasks (Adler et al., 2020).

Some authors propose a definition of citizen science similar to a creative crowdsourcing (Muller et al., 2015), while most of the studies agree with the assumption that citizen science occupies a superior level among the participatory approaches (MacPhail et al., 2020). According to this latter vision, crowdsourcing is an important tool for citizen science but not a research approach on a whole.

A common and statutory definition of citizen science is still missing (MacPhail et al., 2020). Most common definitions distinguish three typologies (or levels) of citizen science: (1) contributory, (2) collaborated, and (3) co-created (Bonney et al., 2009; Newman et al., 2011; Grainger, 2017; Heiss & Matthes, 2017; Schrögel et al., 2019). The distinction of these three types depends on the level of engagement and tasks assigned to volunteers. (1) Contributory refers to projects designed by expert scientists, where volunteered contribution is limited to data collection (Bonney et al., 2009; Newman et al., 2011; Cohn, 2008; Green et al., 2020).

Contributory citizen science can assume consultative function when authoritative entities – such as governmental bodies or institutions – support scientists in research question and research design definition (Ferster & Coops, 2013). (2) Collaborated refers to projects generally defined by scientists, in which volunteers can contribute to refine research design and activities such as data collection and analysis, and dissemination of outcomes (Bonney et al., 2009; Newman et al., 2011; Green et al., 2020). In a socio-hierarchical perspective, stakeholders can replace or work alongside expert scientists in project definition (Ferster & Coops, 2013). (3) Co-created refers to the collaboration of scientists and volunteers from the co-design and co-conceptualization phase, where participants are actively involved in most or all stage of the scientific process (Bonney et al., 2009; Newman et al., 2011; Green et al., 2020). Co-created citizen science can assume transformative functions when a local community leads a project (Ferster & Coops, 2013).

In addition to this traditional schematization, another conceptualization of citizen science proposes: (1) contractual dimension, where a local community employs professional researchers to conduct specific investigations for common concerns (Green et al., 2020); (2) collegial dimension that implies independent research by volunteers submitted to professional researchers for a scientific review (Green et al., 2020). These latter typologies tend to strongly limit the role of expert scientists in the research design process (Green et al., 2020). Beyond this schematization (as illustrated in Figure 2.2), it is possible to assume that citizen science contributes to establish a constant dialogue between communities, stakeholders and experts and support the understanding and engagement of volunteers from local communities into scientific tasks (Bonney et al., 2009; Commodore e t al., 2017).

Typology	Research design	Volunteers' role
Contributory (consultative)	Projects designed by expert scientists *(Bonney et al., 2009)* or by authoritative bodies *(Ferster & Croops, 2013)*	Volunteers' contribution limited to data collection *(Bonney et al., 2009)* or to general consultation *(Ferster & Croops, 2013)*
Collaborated (collaborative)	Projects generally designed by scientists *(Bonney et al., 2009)* or by stakeholders *(Ferster & Croops, 2013)*	Volunteers' engagement extended to refine research design and the whole research activities from data collection to outcomes dissemination *(Bonney et al., 2009)*
Co-created (transformative)	Scientists and volunteers work together in all steps of research *(Bonney et al., 2009)* or local communities take the lead into projects *(Ferster & Croops, 2013)*	
Contractual	Local communities employ professional researchers for scientific investigation *(Green et al., 2020)*.Citizen Science connected to community-based approaches *(Commodore et al., 2017; Adler et al., 2020)*	
Collegial	Indipendent research by volunteers submitted to experts for a scientific review *(Green et al., 2020)*. Marginal extremist positions into scientific community *(Bonney et al., 2016)*.	

Figure 2.2. Citizen science typologies summarizing table.

The conceptualization of citizen science implies a holistic perspective that concerns social inclusion, cultural differences and jurisdictional framework (Schrögel et al., 2019; Green et al., 2020) functional to: (1) empower general public participation in research activities and raise public knowledge and awareness in a context in which citizen science is considered as a pillar of open science in political and socio-economic systems (English et al., 2018; Ignat et al., 2018); (2) contextualize and connect scientific research to social and institutional needs (Wei et al., 2016).

The debate on the definition of the concept of citizen science also focuses on the role played by digital and web-based technologies advances. The use of specific technological tools – such as collaborative database, social media, networking and collaborative technologies – undoubtedly constitutes an added and innovative value for the recruitment, involvement and training of volunteers in scientific research processes (Larson et al., 2020; Lawson et al., 2015; Van de Gevel et al., 2020). Citizen science represents an innovative approach for computer and data science in acquiring, integrating and modelling a massive quantity of data (Voinov et al., 2016; Hochachka et al., 2012). Nevertheless, the use of digital technologies does not necessarily constitute a fundamental requirement for citizen science, although it facilitates and enhances the application of its principles in the context of scientific research.

2.3.2 Differences between Citizen Science and Participatory Approaches

Participatory approaches indicate a set of ways of involving volunteers in scientific research from data collection to co-production and dissemination of results. In their board sense, crowdsourcing and citizen science are part of this set.

Citizen science differs from other participatory approaches in terms of the level of engagement of volunteers. In a citizen science approach, amateur volunteers are in- volved in the research design, data collection and interpretation processes together with experts (Bonney et al., 2009; Buytaert et al., 2014; Newman et al., 2011; Lee et al., 2020; MacPhail et al., 2020; Njue et al., 2019). According to the level of expertise or experience, citizen science can involve participants at various stages of the scientific process (Frigerio et al., 2018), while traditional participatory approaches tend to leverage volunteers, regardless of their own skills. Then, citizen science can modify organizational issues by diversifying tasks of participants with new forms of online or network participations (Frigerio et al., 2018; Haklay et al., 2018). Participatory efforts in a citizen science process are also addressed to build a community of volunteers that cooperate in coordination with experts to achieve specific research goals.

Instead, in traditional participatory approaches, the role of amateur volunteers is generally passive and limited to data collection under the supervision of experts. In some cases, data collection could be unintentional or unaware (Peter et al., 2019). In traditional participatory approaches, volunteers usually act as sensors. The term "participatory sensing" indicates that the role of volunteer participants is limited to sensor activities in a context of research definition and designing under the supervision of experts (Ferster & Coops, 2013). In this context, volunteers are engaged just to collect data with the support of digital technologies or by standard surveys (Van de Gevel et al., 2020; Minet et al., 2017). Experts not only supervise the design and goals of the research, but also the design technological framework and tools. An example of participatory sensing is strictly connected to Volunteered Geographic Information (VGI) (Goodchild, 2007), as a complementary, and in some cases unaware, information provided by volunteers or the general public by their own georeferenced personal devices. In the context of VGI, people act as human sensors, providing information about geospatial context (Goodchild, 2007).

Citizen science and participatory approaches present similarities in searching for new ways of knowledge production (Bonney et al., 2009; Van de Gevel et al., 2020). In the achievement of new sources of knowledge, researchers and experts adopt strategies to increase public understanding and awareness and to make the whole scientific process more participative (Van de Gevel et al., 2020) thanks to the support of web-based technologies and the combination of scientific research and social inclusion purposes (Van de Gevel et al., 2020). Research monitoring programs are usually approached from a top-down data-centric perspective (Kühl et al., 2020). Engagement of people with a different level of expertise and knowledge can contribute to enrich point of views in research activities and enlarge research perspectives (Kühl et al., 2020) by paving the way to citizen science approaches that also consider socio-cultural perspectives (Kühl et al., 2020).

Citizen science also differs from citizen observatories, as an approach for the observation of phenomena for earth and environmental monitoring (Grainger, 2017; Liu et al., 2014). The main difference between the two approaches lies in their own benefits and goals. If citizen science is an innovative approach to scientific research, citizen observatories is a supporting tool for governance and policy in a perspective aimed to create synergies and networks between citizens and stakeholders to solve local policy about environmental issues (Liu et al., 2014). Despite their own different goals (Liu et al., 2014), citizen science and citizen observatories can have many similarities such as methods and tools that improve and stimulate participation and people engagement on the topic of common issues (Grainger, 2017). Citizen science can trust on the support of local communities, but it is not characterizing. Local communities, instead, are characterizing for citizen observatories. The latter can have general regulations but a different implication. Citizen science can have general regulations applicable in every context.

2.3.3 Volunteers' Engagement

Recruitment and Motivations

Recruitment and motivation are two key aspects in setting up citizen science projects. Volunteer recruitment simply consists of the act of finding and retaining non-expert participants for a long-term period (Ferster & Coops, 2013). In a citizen science perspective, recruitment is aimed at building organized groups of volunteers to build active communities around specific research topics. Matching scientific purposes with social and local community needs can make volunteer recruitment easier and stimulate collective participation and collab- oration between volunteers and experts. Therefore, citizen recruitment opens up to new innovative ways to reduce the gap between non-experts and professional scientists and helps experts to produce knowledge for purposes that matter to the general people (Adler et al., 2020).

A community is a complex group that can involve different kinds of actors such as, (1) expert scientists in the role of coordinators, (2) decision makers (3) stakeholders and (4) the general public or citizens (Voinov et al., 2016; Kühl et al., 2020) that share a common vision of society and organization (Kühl et al., 2020). However, different typologies of participants within the community can imply a different level or stage of involvement within the participatory process according to expertise, experience, and personal interests (Voinov et al., 2016). The participatory process, in fact, is articulated in different steps: envisioning and goal settings, model formulation, data collection and cross-checking, model application and evaluation of outcomes (Voinov et al., 2016).

Challenges in recruitment activities usually concern the lack of volunteer interest or of participant diversity (Quinlivan et al., 2020) and the lack of familiarity with science, socio-political and jurisdictional framework limits (Buytaert et al., 2014; Heiss & Matthes, 2017). Social interactions, frequent communication between participants and stakeholders, enjoying the outdoors and a frequent call to action are tools for long-term recruitment and keeping the motivation of participants high (Newman et al., 2011; Larson et al., 2020; Groulx et al., 2017; Commodore et al., 2017; Cunha et al., 2017). The frequent call to action and motivation can be stimulated by gamification of activities, feedback by email from experts, the use of social media and participation rates (Buytaert et al., 2014; Voinov et al., 2016; Green et al, 2020). These tools not only stimulate communication between experts and non-experts, but also provide opportunities for social interactions within the participants' community, increasing their awareness and motivations (Green et al., 2020). Recruitment and motivational methods can be enhanced through partnering with existent organizations – such as civic groups, neighborhood organizations, target communities – that can support long-term activities (Ferster & Coops, 2013). Recruitment activities tend to include volunteer motivation in participatory processes, considering human behaviors, cultural and social attitudes and personal experience (Jordan et al., 2015; Grainger, 2017), even if these aspects can be at the origin of biases and the heuristic mechanism (Voinov et al., 2016). Understanding motivations and human behaviors is a critical area of investigation and represents an integrated part of research design in citizen science projects (Nardi et al., 2022; Van de Gevel et al., 2020).

Motivations at the base of volunteer recruitment and engagement are: (1) personal interest (Bonney et al., 2009; Crain et al., 2014); (2) scientific knowledge for the better understanding of their environment or to gain political leverage (Buytaert et al., 2014); (3) improving relationships between people, institutional actors and stakeholders (Buytaert et al, 2014; Voinov et al., 2016) aimed at social learning and co-management of common resources and goods (Villaseñor et al., 2016); (4) promoting joint action and civic participation on environmental topics with socio-economic and cultural implication or that involves socio-organizational aspects (Jordan et al., 2015; Peter et al., 2019; Lee et al., 2020; Adler et al., 2020; Van de Gevel et al., 2020; Commodore et al., 2017).

Volunteers' motivations may vary according to their level of expertise or personal experience. Neophytes or amateurs with no expertise can be motivated by altruism, curiosity to a specific research topic, curiosity to challenging their capabilities, improvement in awareness, learning more about something familiar (Grainger, 2017; Van de Gevel et al., 2020; Bordogna et al., 2016) or the opportunity to simply have fun (Grainger, 2017). People with a minimum level of expertise are, usually, motivated by a desire to share their knowledge, contribute to science (also only with data collection in support of scientific activity), join a community or contribute to social development (Grainger, 2017; Van de Gevel et al., 2020; Bordogna et al., 2016). Pride and prestige, especially, move to participation authorities or authoritative bodies (Bordogna et al., 2016).

Keeping high volunteer motivation implies a long-term strategy of engagement. To reach this goal, expert recruiters have to consider public gratification (Newman et al., 2011; Bordogna et al., 2016). Volunteers must constantly feel that they have an active role within citizen science projects. A dash- board of data visualization, frequent call to action by email, sharing information with social media, gaming activities and ranking systems are fundamental tools for keeping high participation and motivation by giving constant feedback on volunteers' work and on their necessary role in achieving research objectives (Buytaert et al., 2014; Voinov et al., 2016; Newman et al., 2011; Grainger, 2017; Van de Gevel et al., 2020; Green et al., 2020; Bordogna et al., 2016).

Community Building and Online Communities

Citizen science projects acquire more value when the scientific question has correspondence with local (environmental) issues and meets social and cultural odds (Adler et al., 2020; Cunha et al., 2017; Kankanamge et al., 2019). In this perspective, volunteer engagement acquires a meaning around the sense of community and belonging. The interconnection between the community-based approach and citizen science is aimed at addressing research questions and decision making to specific needs of communities (Commodore et al., 2017). Local community participation in citizen science activities helps to reduce social and environmental disparities and enhances the role of communities in research and decisional processes (Commodore et al., 2017). Community-based monitoring can be considered as a part of citizen science in which non-expert citizens, authorities, stakeholders and scientists can collaborate to respond on common concerns (Conrad & Hilchey, 2011).

Social inclusion and dialogue between expert scientists and volunteers are two pillar characteristics of citizen science approaches. Experts usually care about the research design, recruitment, engagement, training of volunteers and finally the outcomes dissemination. The term “experts” usually indicates people with an academic or scientific background, able to conduct scientific research (Buytaert et al., 2014). In this perspective, the category of experts does not include people with expertise or professional experience in a specific task. The latter composes the vast and heterogeneous group of volunteers, defined as amateurs. Initially qualified as a simple citizen with no academic qualification or expertise (Fester & Coops, 2013) or considered as a human sensor, thanks to the support of personal digital devices (Goodchild, 2007), advances in citizen science usually distinguish different groups of amateurs based on their expertise or engagement level: (1) neophyte, with no official background on the research topic and acts individually for altruism or curiosity; (2) interested amateur, with self-experience in the research topic or some training provided by experts; (3) expert amateur/professional, very familiar with the topic but external to academic and scientific context; (4) expert authorities, that is governmental or public agencies (MacPhail & Colla, 2020; Bordogna et al., 2016). Discovering differences among amateur participants is fundamental for organizing tasks and assigning roles within citizen science projects.

The implementation of web-based technologies into citizen science approaches gives new perspectives for engagement enlarging participation from physical to virtual spaces. Enhancing the role of online communities in citizen science approaches is a challenging topic. Social media and digital technologies, in general, are emerging tools to recruit, engage and motivate organized people in achieving a specific scope (Van de Gevel et al., 2020). Social media may make communication between experts and volunteers easier and, among the latter, contribute to build communities by a constant data and information exchange (Green et al., 2020). Involving online communities into the citizen science approach implies a new form of participant organization around (1) remote work teams, (2) collaborative task management, (3) management of the dynamic division of labor, and (4) communication with large audience

(Ignat et al., 2018). Therefore, engagement of online communities may present limits in terms of data validation and reliability of participants (Vasileiadou, 2015).

Crowdsourcing

Crowdsourcing is an activity to obtain data or information from a large number of people by the use of web-based technologies (Voinov et al., 2016; Muller et al., 2015; Minet et al., 2017). Crowdsourcing consists of the externalization of repetitive and simple tasks to the non-expert public, aimed at data collection from volunteers (Lahoz et Schneider, 2014; Welvaert et al. 2016; Minet et al., 2017; Kankanamge et al., 2019). It could be considered as a valid tool for engaging people and obtaining data and information at a low cost and rapidly at real-time (Muller et al., 2015; Minet et al., 2017).

Crowdsourcing is an emergent tool in research activities aimed to cover the lack and scarcity of information on the strategic field as the environmental and geographic field, affecting the organization of volunteers' and attribution of tasks (Zheng et al., 2018; Minet et al., 2017). Constant availability of information is essential in designing and managing activities (Zheng et al., 2018).

Including crowdsourcing as a method of citizen science means that the latter has a multilevel definition regarding the grade of participation and engagement (Bonney et al., 2009; Zheng et al., 2018). Citizen science refers to volunteers conducting science, while crowdsourcing refers to volunteers giving data and resources (Welvaert et al., 2016; Lee et al., 2020), but they are not involved in research activities (Miller-Rushing et al., 2012).

Unlike citizen science, crowdsourcing activities do not necessary imply the active engagement of people but can be conducted with a passive contribution from a sensor- installed network, the Internet of Things or internet technologies in general (Zheng et al., 2018). Crowd-sourcing data are less accurate than official measurement tools but guarantee most spatiotemporal coverage that could be complementary (Zheng et al., 2018). If citizen science needs to recruit people to conduct its activities (from data collection to research design), crowdsourcing can only make use of unintentional contributions provided not only by citizens, but also by sensors and IoT (Zheng et al., 2018; Welvaert et al., 2016).

Crowdsourcing activities mainly use two categories of tools: (1) a sensor installed by citizens with authoritative supervision; (2) mobile devices for either intentional or unintentional collection (Zheng et al., 2018) as, for example, public social media content. In this latter case, the use of data is anonymous (Skarlatidou et al., 2019). The use of technologies in citizen science, instead, is intentional and aware under an agreement between different users and stakeholders that take part in projects.

2.3.4 Tools

Digital Technologies

Digital technologies usually refer to mobile personal communication devices (MPCDs), such as a camera, microphone, GPS and data storage devices (Ferster & Coops, 2013; Grainger, 2017; Green et al., 2020). New digital technologies are tools for low-cost, more geographical and time series coverage (Njue et al., 2019) and that complement traditional instruments of data collection (Buytaert et al., 2014).

Personal devices provided with a camera and GPS offer a new scale and perspectives of information (Ferster & Coops, 2013). The advances in digital technologies and consumer electronics offer new opportunities to gain data not only from experts, but from the general public as well, who can contribute to data collection and provision with their own personal devices that can guarantee a broader spatial and temporal coverage (Ferster & Coops, 2013; Simoniello et al., 2019). These advances contribute to create a distributed network of sensors spread around the geographic space and to constantly operate during time and at a different scale and perspectives (Ferster & Coops, 2013; Green et al., 2020).

Firstly, researchers use digital technologies in citizen science projects to facilitate and enlarge the participation of general users because of non-intrusive characteristic, commonly used in the daily life of citizens (Lahoz & Schneider, 2014; Frigerio et al., 2018; Tulloch et al., 2013; Andrachuk et al., 2019). Secondly, digital technologies are catalysts for community-based participatory initiatives, enhancing communication between experts, stakeholders and citizens and organizations within local social networks and online communities (Heiss &

Matthes, 2017; Andrachuk et al., 2019). On the organizational level, advances in digital technologies improve data collection methods set up on the direct handling and sharing of information (Andrachuk et al., 2019). The use of digital technologies also allows access to additional and auxiliary information, such as insights on real-time and location-based information as in the case of Volunteered Geographic Information (VGI) (Newman et al., 2011; Goodchild, 2007). Furthermore, experts use digital technologies for the assignment of roles and tasks within the organization according to different levels of participation such as: data collectors, designers of problem definition and data collection methods, data framing interpretation and knowledge sharing (Andrachuk et al., 2019).

Web-Based Technologies

The development of technological systems and web-based services offers new opportunities for a better engagement of volunteers by distributing to them and to experts, infrastructural solutions for connecting devices and data storage (Buytaert et al., 2014; MacPhail & Colla, 2020; Marchezini et al., 2018). Thanks to modern technologies, data can be collected on unprecedented scales even with limited funds (Frigerio et al., 2018).

The spread of internet technologies has changed the landscape of information avail- ability and the way people use to interact and set attitude and behavior (Skarlatidou et al., 2019) and foster the development of participative activities around citizen science approaches (Minet et al., 2017). The use of web-based technologies facilitates the interaction between people of different ages, geographic origins and different motivation and goals (Skarlatidou et al., 2019). These interactions, instead, pose some reflections about how technological tools can be used and pose some issues about relationship and human-computer interactions (HCI) (Skarlatidou et al., 2019; Van de Gevel et al., 2020) and other reflections on user experience (UX). In order to facilitate HCI and UX, the design is the first approach. Design must reflect cultural and environmental characteristics that introduce users into research activities and reduce the technological knowledge gap and, in any case, also availability and coverage (Skarlatidou et al., 2019). Developing platforms for data sharing and visualization facilitates the retaining and motivation of volunteers (Skarlatidou et al., 2019). HCI and new communication media are tools for facilitating stakeholder engagement and for enhancing the smart adapt- ability of organizational and decision processes by inserting human interaction into process modelling (Voinov et al., 2016; Van de Gevel et al., 2020).

Social Media

The pervasiveness of social media is changing the way users interact and the ability to build social networks (Dickinson et al., 2012; Dickinson et al., 2013). The successful design of internet technologies and social media platforms influences the way users interact and the capacity to create online groups of volunteers (Frigerio et al., 2018; Dickinson et al., 2012; Dickinson et al., 2013). These aspects offer, first, new ways of data collection and implementing research models set up on a constantly shared and updated information exchange between experts, stakeholders and volunteers (Voinov et al., 2016). This pervasiveness makes social media platforms as interesting, potentially fundamental, tools within scientific research activities to reach and engage an increasing number of participants able to collect an unprecedented amount of real-time data, expanding the geographic coverage of information (Greshake Tzovaras et al., 2019; Lopez et al., 2019; See, 2019). Similarly, social media platforms can be useful tools to simplify organizational steps of citizen science projects, such as recruitment and task assignment (Frigerio et al., 2018; Dickinson et al., 2013), outcomes dissemination and call to action (Newman et al., 2012). Social media can also be used as mediation tools between experts and volunteers to understand participants' behavior within the social and environmental context of action (Dickinson et al., 2013; Lopez et al., 2019). In fact, social media can give direct and unfiltered information on aspects concerning both personal and collective attitudes and perceptions (Lopez et al., 2019).

However, the use of social media data, in the context of citizen science, remains limited and experimental, due to the potential biases deriving from the cognitive perception of participants (Voinov et al., 2016; Lopez et al., 2019).

Gamification

If digital devices and smartphones are widely considered as consolidated tools for dealing with citizen science activities, gaming represents a new innovative frontier for long-term engagement of volunteers and keeping the motivation of participants high (Newman et al., 2012).

Gamification contributes to what is defined as “distributed thinking” (Adler et al., 2020) and is a tool for motivating volunteers in data collection and participation activities by designing interactive and dynamic graphic interfaces (Skarlatidou et al., 2019).

Serious games and gamification are two pervasive and innovative tools in the communication of science and in engagement of citizen scientists (Quinlivan et al., 2020; Aubert et al., 2018). They reflect the emotional and motivational aspect of citizen scientists (Aubert et al., 2018) and are promising tools for teaching concepts, distributing training and skills, communicating scientific topics and promoting participatory modelling (Voinov et al., 2016; Aubert et al., 2018). The main potential of gaming is its leisure and fun characteristic that can stimulate non-expert participation (Aubert et al., 2018).

Serious games encourage participants to evaluate their actions, raising awareness of the consequences by creating a simulated scenario and offering an engaging and challenging frame (Aubert et al., 2018). Simulated scenarios may be functional in understanding cognitive processes in the context of evaluation of alternatives and decision making (Aubert et al., 2018).

Artificial Intelligence (AI)

Artificial Intelligence (AI) represents an innovative tool for advances in citizen science approaches. Reliability and accuracy of observations are important issues in data collection with personal devices. AI can contribute to data collection and validation by developing algorithms for data comparison or sampling (Green et al., 2020). The use of artificial intelligence, drones and sensors can help to convert citizens’ and volunteers’ data into useful information by comparing VGI and user-generated contents (UGC) from camera and personal devices to official data (Ryan et al., 2018). AI supports the definition of data protocols and sampling and the improvement of citizen science efficiency.

Artificial Intelligence is frequently used in ecological and environmental citizen science monitoring to identify elements provided by volunteers in the form of digital data, such as images or videos (Green et al., 2020). The use of AI in citizen science monitoring aims to improve efficiency and classification accuracy by detecting volunteered observations and connecting them to samples from traditional monitoring tools (Green et al., 2020).

Developing AI solutions for reducing errors and biases of volunteers' contributions support validity of citizen science outcomes and data quality validation (Green et al., 2020). Overall, the integration of citizen science and AI technology can be used to help maximize the amount of data that can be collected and processed efficiently, while simultaneously engaging and informing people about professional research activities and their value for society and decision-making processes that affect socio-economic and environmental systems (Green et al., 2020).

2.3.5 Data

Data Types

Most challenges and opportunities of data collection in citizen science approaches are the need to have a larger spatial coverage and constant updating time series (Buytaert et al., 2014; Njue et al., 2019; Minet et al., 2017; Quinlivan et al., 2020; Simoniello et al., 2019; Loss et al., 2015).

Citizen science implies the integrated use of data types from different sources to improve research models and support decision-making processes based on constant and widespread monitoring of phenomena: (1) official data, (2) volunteered data, (3) incidental data (Criscuolo et al., 2013). Official data refers to authoritative data produced by experts, such as researchers, professionals and technicians in the context of their professional or institutional activities, collected with specific tools under reward. Volunteered data are related to volunteers' activity coordinated by experts who provide guidelines for data collection in the context of citizen science in general for purely scientific purposes without rewards (Jordan et al., 2015; Criscuolo et al., 2013). Incidental data refers to the whole crowd data available on the web. Incidental data usually refer to information – usually unstructured – furnished by amateurs for different purposes distributed in forum or social media groups and pages (Criscuolo et al., 2013).

Platforms and visualization of results (1) enhance the reliability and efficiency of citizen science projects (Buytaert et al., 2014), (2) facilitate exchange and collaboration in modelling processes between different actors (Voinov et al., 2016), (3) build joint scenarios and (4) formulate a shared hypothesis and research design (Buytaert et al., 2014; Minet et al., 2017). In addition, the development of visualization platforms can facilitate engagement and increase the long-term motivation of volunteers because of the immediacy and transparency of communication.

Developing data collection and visualization tools is fundamental for citizen science research approaches to obtain knowledge and useful information to support decision- making processes (Hochachka et al., 2012).

The Role of Geographic Information: VGI and Participatory GIS

Among the different types and sources of data for citizen science, Volunteered Geo- graphic Information (VGI) occupies a particular section, because of its specific characteristics about geographic information and the opportunity to find contribution in geospatial context. Advances in GIS and VGI with personal devices support a holistic participatory approach in research and decision-making activities (Haklay et al., 2018). VGI can facilitate the contextualization and the distribution of information linked to environmental and social issues, as a context of origin of contribution (Goodchild, 2007). VGI and participatory GIS are typically useful in investigating human behavior in the geographic and environmental context (Nardi et al., 2022; Haklay et al., 2018; Bordogna et al., 2016; Pricope et al., 2019). Mapping activities with participatory GIS (PGIS) furnishes supplement data for a better understanding of geospatial context and factors (Voinov et al., 2016). PGIS facilitates the communication between the base of group decision systems, supports the creation and exchange of new knowledge by analyzing impacts of geospatial factors in modelling processes, provides a transparent and user-friendly visualization of data and results with dynamic maps (Voinov et al., 2016; Haklay et al., 2018). Volunteered efforts in geographic data collection and production have redefined the traditional roles of experts in mapping activities (Goodchild, 2007). VGI in research is a hot topic related to the development and advance in web technologies for involving people and obtaining several types of data with geographic location which helps to contextualize the information available (Bordogna et al., 2016). VGI contents are the pillar source in the earth citizen science framework (Bordogna et al., 2016), such as object identification, measurements, transcriptions and corrections of existing data, indications and complementary indications from volunteers (Bordogna et al., 2016). VGI can be classified as: (1) automatic and implicit, when users provide data unintentionally by the use of software or application that use GPS o geolocation tools; (2) manual and implicit, related to social media, gaming and web behavior and trends in general; (3) manual and explicit, when volunteers are aware of the objective of their action; (4) automatic and explicit, when users are aware and furnish VGI by software or specific applications with GPS (Bordogna et al., 2016).

2.3.6 Outcomes and Opportunities

Evaluation of social learning and outcomes is a complex task. Socio-organizational and economic impacts of citizen science are not direct but may give significant feedback on the motivational aspect at the base of engagement. Citizen science has social and educational benefits in terms of raising knowledge, education and awareness around public interest topics (Dickinson et al., 2012; Lawson et al., 2015; Adler et al., 2020; English et al., 2018; Tulloch et al., 2013; Loss et al., 2015). Citizen science offers new methods and tools for the generation of scientific knowledge, motivation of public engagement with scientific research in common concerns (Loss et al., 2015) and provision of scientific education (Dickinson et al., 2012; Lawson et al., 2015; Tulloch et al., 2013). Citizen science represents a common space for socializing; it creates a sense of belonging that contributes to participants' performance and outcomes (Crain et al., 2014) by improving efficiency, effectiveness and the scope of research processes (Van de Gevel et al., 2020). Citizen science creates a space for social inclusivity, dialogue between stakeholders and allows people to express themselves by giving a voice to non- experts (Van de Gevel et al., 2020), starting from personal and community interests related to a specific local issue, such as resource management or the optimization of decisional processes (Frigerio et al., 2018). In this way, citizen science increases the research capacity and efficiencies of crowdsourcing, social knowledge, empowers communities and engages policy and decision making (Lahoz & Schneider, 2014; Muller et al., 2015; English et al., 2018). Social inclusion and empowerment of communities depends on the ability of research activities to be inclusive and open to local communities' perceptions and socio-cultural instances (Lahoz & Schneider, 2014; Van de Gevel et al., 2020; Groulx et al., 2017; Cunha et al., 2017).

Social inclusivity – derived from citizen science activities – contributes to mitigate conflicts around environmental and resources management (Frigerio et al., 2018). It also contributes to improve the economic situation of participants by giving them knowledge and tools for managing local issues (Frigerio et al., 2018). Citizen science also contributes to the professionalization of volunteers into scientific context (Crain et al., 2014). Finally, it promotes to reduce the gap between professional scientists and people outside the academic context (Frigerio et al., 2018).

Additional benefits of citizen science can be recognized into the detection of rare and unpredictable events (Lawson et al., 2015) and the possibility of discovering something new accidentally (Tulloch et al., 2013). These characteristics allow to build and constantly update data and procedure models that positively impact on organizational and logistical aspects of research and decision processes (Lawson et al., 2015).

The benefits in citizen science are measurable into equitable decision making and the facilitation of dialogue in policy making, by making citizens aware, on the one hand, and taking into consideration the communities' proposals and problems on the other (Buytaert et al., 2014; Peter et al., 2019). Citizen science represents an occasion of dialogue between citizens, local communities, stakeholders, institutions and scientists (Commodore et al., 2017; Cunha et al., 2017) in a vision in which communities address research questions, express concerns, while scientist offer an answer on the base of citizen contribution in covering data gaps, and authorities take decisions (Kankanamge et al., 2019).

Citizen science projects can rely on the community-based approach, in order to guarantee social well-being, because it links community needs to the scientific framework and gives voice to general people usually not considered into research activities (Bonney et al., 2016; Lee et al., 2020; Van de Gevel et al., 2020; Tulloch et al., 2013). In this perspective, citizen science gives the potential to generate social capital and take collective action (Cunha et al., 2017), strictly connected to the context and place-based knowledge and social bonding (Groulx et al., 2017). Citizen science offers the opportunity and concrete context to enhance stakeholder participation by promoting communication and engagement activities coordinated by experts (Groulx et al., 2017). It means that citizen science can coordinate citizens' efforts in decision and policy-making processes (Lahoz & Schneider, 2014; Groulx et al., 2017). Linking science with community needs can increase citizen participation and keep motivation high for the long term (Bonney et al., 2016). In this perspective, citizen science makes the research activities societally relevant (Lee et al., 2020; Cohn, 2008) and develop large-scale and long-term monitoring under scientific supervision in order to support and plan decision-making processes (Lee et al., 2020).

Indirectly, citizen science helps social and economic research because it investigates behavior behind action taken (Tulloch et al., 2013). Citizen science implies deep personal and social changes in behavior because it imposes self-reflection and examination of belief systems at the base of socio-cultural organization systems and economic behavior (Groulx et al., 2017). Citizen science poses, also, deep reflections on the cultural context of application and general organizational issues in order to develop and promote a participation culture at a national or regional scale as a structural methodology for the monitoring and organization of environmental governance supported by bottom-up observations, by integrating data and expertise and the stakeholders' network (Kühl et al., 2020). Citizen science programs can enhance decision-making processes by stakeholders and governments (Cunha et al., 2017) through the decentralization of organizational processes and new management towards public engagement and awareness (Voinov et al., 2016; Tulloch et al., 2013). An indirect benefit of citizen science is promoting social justice and equality and improving education around common concerns (Ryan et al., 2018).

2.3.7 Limits and Challenges

Lack of Standardized Protocols

Citizen science presents limits and challenges mainly related to the lack of standardized and universal protocols applicable to multiple case studies (Adler et al., 2020; MacPhail & Colla, 2020). Research design and protocols often adapt to specific case studies or to the solution of single issues limited to restricted geographic or social contexts (Loss et al., 2015). A lack of standardization in research design limits the possibilities of comparison between different case studies and the application of large-scale citizen science models (Adler et al., 2020; Loss et al., 2015). These limits can generate problems in terms of methodological rigor, data collection, definition of activities and coordination between volunteers (MacPhail & Colla, 2020). The absence of standardized protocols or a universal research agenda specific to citizen science can threaten the elaboration of a new solid relationship, practices and interaction (Vasileiadou, 2015). Due to different models and points of view, methodological approaches hamper the development of a unique protocol or research agenda (Vasileiadou, 2015).

Human perception and socio-cultural background may affect data collection activities and the fulfillment of tasks assigned to the volunteers (Voinov et al., 2016; Heiss & Matthes, 2017; Adler et al., 2020; English et al., 2018; Simoniello et al., 2019; Lopez et al., 2019). Levels of education or training and cognitive biases can threaten the validity and reliability of volunteers' observations (Commodore et al., 2017; Conrad & Hilchey, 2011). Subjective perceptions and biases not only influence interpretation and dissemination of results (English et al., 2018), but also may have potential negative consequences in economic, human and environmental concerns (Ryan et al., 2108; Conrad & Hilchey, 2011).

Citizen science needs the provision of adequate infrastructures in order to support communication, (online) training (Simoniello et al., 2019), storage of data collected, to offer analysis and standardize program evaluation (Newman et al., 2011). Appropriate technology helps citizen science projects. Internet and smartphones are fundamental tools to facilitate the participation, but they are not a warranty of data quality and training is needed for the correct use of these technologies in citizen science tasks (Lahoz & Schneider, 2014; Frigerio et al., 2018; Larson et al., 2020; Lawson et al., 2015; Andrachuk et al., 2019). The success of participatory approaches, as crowdsourcing and citizen science, does not rely only on technological advances, but also on the capacity to engage people and foster cooperation and coordination between participants and stakeholders around common community concerns (Zheng et al., 2018).

Citizen science presents socio-economic challenges in terms of controversies, insufficient funding, and barriers to participation related to social marginalization or political and jurisdictional impediments (Buytaert et al., 2014; Lahoz & Schneider, 2014; Van de Gevel et al., 2020; MacPhail & Colla, 2020; Minet et al., 2017). Citizen science may usually involve just a specific segment of society, reducing and underestimating other groups that can offer several perspectives on a specific concern (Adler et al., 2020). Some projects reflect the same values and opinions and offer a distorted vision of the local community as a whole (Adler et al., 2020). Equal social representation in citizen science activities affects volunteers' retention and contributes to keep motivations of participants high for long-term goals (Adler et al., 2020). Marginalization usually takes origin from social, political and jurisdictional (such as digital divides) issues that limit the participation to specific groups and exclude others (Buytaert et al., 2014; Commodore et al., 2017; Andrachuk et al., 2019). Funding issues constitute an additional marginalization factor that hampers not so much data collection, but especially training, monitoring and quality control (Cunha et al., 2017).

Finally, other challenges derive from data sensitivity and volunteers' privacy typical of research activities in general (Heiss & Matthes, 2017). The main issue regards the ownership of data and the way in which data can be used and who can use them (Lee et al., 2020). These open questions have an impact on ethical concerns (Greshake Tzovaras et al., 2019). Digital and web-based technologies have radically changed relationships and interaction among volunteers in participatory approaches (Skarlatidou et al., 2019). This poses a serious reflection about privacy concerns in research activities as a potential barrier to public participation (Skarlatidou et al., 2019).

Data Validation: Quality and Uncertainties

Data validation is a fundamental and crucial step for determining reliability in citizen science projects (Voinov et al., 2016; Adler et al., 2020; MacPhail & Colla, 2020). It consists in the definition of data quality related to accuracy and consistency of observations provided by volunteers. Data quality is strictly connected to skills and training of participants (Adler et al., 2020; Simoniello et al., 2019), and to the appropriateness of the scientific method adopted (Cunha et al., 2017). Errors in data collection, in fact, generally depend on (1) volunteers' biases, and (2) the lack of standardization in data collection or data structure. Data quality also depends on the support of metadata description (Ferster & Coops, 2013; English et al., 2018).

Errors in participatory data collection activities can be aleatoric, when referring to statistical uncertainties or epistemic when uncertainties depend on the lack of knowledge (Voinov et al., 2016). Errors in data collection can be classified as (1) random, (2) systematic and (3) representative (Lahoz & Schneider, 2014). Random errors can be reduced by averaging methods (Lahoz & Schneider, 2014). Systematic errors are related to human biases and can be excluded when recognized (Lahoz & Schneider, 2014). This kind of error is common when data collection activity is based on social media platforms, where user activities can be deceptive or misleading (i.e., troll) (Lopez et al., 2019). Social media data can also constitute problems related to data silos and in merging and comparing observations (Greshake Tzovaras et al., 2019). Representativeness errors depend on technical observation methods and tools (Lahoz & Schneider, 2014). Uncertainties can depend on a lack of participants' objectivity derived from subjective issues or by the adoption of inaccurate measurements (Quinlivan et al., 2020). Another source of errors can be derived from the digital divide that hinders data transmission and causes irregular intervals in time-series and geospatial coverage of citizens' contributions (Buytaert et al., 2014; Zheng et al., 2018; Quinlivan et al., 2020). The availability of strong and widespread digital infrastructures is fundamental for volunteered observations' validation and reliability. The availability of digital infrastructure is predominantly spread in urban and suburban areas, but less in marginal and rural areas. This issue implies that volunteered observations can be focused on a specific context and make the application of citizen science difficult at a large scale. Weakness in internet connection or GPS signal implies the lack of balanced and well-spread information or approximate and fragmented data where the internet connection or GPS signal is weak (Ferster & Coops, 2013; Quinlivan et al., 2020).

Challenges in data validation regards spatial and temporal resolution, cost, accessibility, availability, uncertainty and dimensionality (Zheng et al., 2018). Definition of specific paradigms is useful for providing a priori principles for citizen science activities and data validation. Some factors, such as the spatio-temporal domain, socio-cultural organization or jurisdictional framework, can influence the adoption of paradigms and practices (Wei et al., 2016).

Definitions of ex ante or ex post sampling methods and standardization protocols constitute general solutions to deal with data validation (Grainger, 2017; Vermeiren et al., 2016). Ex ante strategies imply the adoption of standard metadata, automatization of data collection tools, controlled vocabulary and adequate training of volunteers. Adoption of standardization models and protocols for data collection are functional to define a specific quantitative research question and address volunteers in data collection (Newman et al., 2011; Larson et al., 2020; Cunha et al., 2017; Loss et al., 2015; Bela et al., 2016). The establishment of a paradigm as the term of comparison for data quality and validation through sampling schemes aims to reduce errors and biases (Ferster & Coops, 2013; Commodore et al., 2017). The adoption of a data model, such as predefined classes, could help to obtain complementary and useful information to integrate into models at the base of research activities and decision-making processes (Minet et al., 2017). Standard ex ante models permit replication, community checking, training, profiling, reputation and finally discard outliers (Minet et al., 2017).

Ex post strategies are pivoting around ranking volunteers' contribution, data mining, enrichment and comparison with external knowledge and professionals (Frigerio et al., 2018; Bordogna et al., 2016). In this latter case, the adoption of comparison models or quality indicators as ISO standards facilitates data validation procedures (Bordogna et al., 2016). Online data forms speed up the process of sampling and validation (Bonney et al., 2009; Vermeiren et al., 2016) by enhancing the cooperation between volunteers and experts aimed at solving data harmonization and homogenization issues using web 2.0 technology (Lawson et al., 2015; Criscuolo et al., 2013) and by the adoption of validation methods elaborated by experts (Simoniello et al., 2019). Another validation strategy consists in gathering a large amount of data in order to obtain several terms of comparison for data sampling and research of standard protocols (Hochachka et al., 2012; Minet et al., 2017). Gathering large amounts of data includes not only the quantity, but also a wide geographic scale of collection (Dickinson et al., 2012). Data enrichment passes also through the comparison of coupled data and data interlinks (Crain et al., 2014). Gathering a large amount of data requests the involvement of distributed networks of volunteered data collectors (Crain et al., 2014). Their contribution is important not only for gathering a large amount of data, but also to gain complementary information for the contextualization of information into social, cultural and economic frameworks (Crain et al., 2014). Another possible solution for data validation is randomization (Loss et al., 2015). Randomization consists in generating data representative for a specific field, period or location in order to obtain a sample of information (Loss et al., 2015). Randomization allows research to address a general question and design a sample scheme (Loss et al., 2015) in order to verify quality and outcomes (Newman et al., 2011). Standardization protocols, randomization and gathering vast amounts of data help to build validation models through comparison and integration with authoritative data (Criscuolo et al., 2013). In this way, data interpolation and simulations are two common methods for testing data reliability and quality (Buytaert et al., 2014; Lahoz & Schneider, 2014).

Data quality validation implies the adoption of a transdisciplinary approach, including social scientists – in order to investigate behavioral and background context – and statistical and computer scientists for protocol definition and data sampling (Commodore et al., 2017; Hochachka et al., 2012; Schröter et al., 2017). New statistical model and visualization tools could represent a solution for enhancing data quality (Adler et al., 2020). Integrating computer science into citizen science approaches helps to make efficient data entry and elaboration activities (Adler et al., 2020; Commodore et al., 2017). Especially, introducing statistical weighting is functional to rank volunteers and weigh their contribution (Lee et al., 2020). Statistical models help also to find random errors or statistical biases (Lee et al., 2020). Procedures for enhancing data quality and validation within a citizen science project include the supervision of experts and cross-checking activities among citizen scientists (Lee et al., 2020; Schröter et al., 2017).

2.4 Discussion on meta-review analysis

The meta-review points out a variety of approaches and methods adopted in citizen science. The transdisciplinary application of citizen science provides a wide range of methods as useful insights for overcoming the single disciplinary fields towards an integration of knowledge and research tools within a general theoretical framework. The transdisciplinary framework constitutes an advantage, also than a necessity, for investigating many implications of citizen science. This implication regards computer scientists for technological structure; social and behavioral scientists for investigating relationship between stakeholders and participant and their cultural and environmental background; experts on organization studies for investigating the organization and recruitment of volunteers and to analyze changes in co-production and co-design processes; then, experts on the specific field of applications (biologists, hydrologists, ecologists, geographers and so on).

These aspects emerge the importance of organizational studies and the potential role of online communities in carrying on a citizen science project by taking advantage of the wider spread and availability of digital and personal mobile sensors. The pandemic situation of COVID-19 also imposes a serious reflection on finding a new and innovative model to engage, motivate and organize people in giving contribution about common concerns – such as climate change, environmental challenges, the Water-Environmental-Food-Energy (WEFE) Nexus, resources management, monitoring and sustaining urban planning and services or reaching, at local scale, the Sustainable Development Goals (SDGs) adopted by the United Nations by promoting a collective call to action. Concerns that threaten our societies and have a strong impact on socio-economic systems, productions (industrial, agricultural) and cultural lives and wellbeing.

This review also highlights the evolutionary characteristics of the concept of citizen science. Starting from an effort of democratization on science through data collection, most recent perspectives enlarge the engagement to all the steps of research activities, from data collection to outcomes dissemination. The heterogeneous nature of volunteers and different motivations and behaviors at the base of their recruitment, make for more complexing citizen science activities, diversifying tasks and goals.

In a definition of a conceptual framework of citizen science, three pivotal points are fundamental: (1) data collection, (2) behaviors investigation and (3) building new models. The adoption of data collection methods aims to broaden the time and space coverage of available information, integration of data models and finally obtaining feedback from citizens. Behaviors investigations shed light into volunteers' background at the base of their choice and attitudes. Behaviors investigations may also shed light onto impacts of the decision and organizational model, both on the individual and societal level. Finally, citizen science approaches allow the investigation on relationship and integration between socio-economic and environmental systems for a new management of resources and optimization in terms of sustainability. Citizen science also allows finding shared solutions with the adoption of scientific methods for common and societal concerns. It gives constant feedback on adopted solutions and research design through an innovative organizational framework that includes scientists, stakeholders and citizens.

This meta-review analysis has shed light on key aspects of citizen science, as a participatory and inclusive bottom-up model on the co-design and co-production of knowledge. The heterogeneity of citizen science inputs and practical applications allow to identify a series of general requirements useful for the setting of participatory and inclusive models, with a view to continuous and constructive collaboration between experts and society.

Firstly, collaboration between experts and volunteers is based on the definition of a shared research question. A research question should intercept social needs and be oriented towards the solution of empirical problems. Researchers usually play a predominant role in this respect, for obvious reasons, related to the level of expertise.

Secondly, this meta-review analysis highlighted the varied typology of participants in citizen science processes. Each volunteer can be motivated by particular motivations and interests, and be the bearer of different and conflicting social and cultural demands. Researchers and volunteers should, therefore, work together to find a synthesis of views developing a common strategy towards targeted and specific objectives. They should, thus, identify defined target groups and set organizational models based on the characteristics, motivations and competences of the different groups of participants. Inclusiveness and bottom-up participation are two pillars in citizen science.

It does not mean that roles within an organization are necessarily equal and interchangeable. The role and position of each participant must reflect personal knowledge, skills and abilities. An organization active in citizen science includes a structure of roles divided between experts and volunteer participants. The latter, however, can benefit within the organization in terms of professionalization, acquisition of skills and awareness, through the possibility of continuous training, dialogue and open discussion with experts and stakeholders.

Thirdly, this meta-review analysis highlighted the advantages of digital technologies for active and inclusive bottom-up participation, which can be measured, above all, in: (1) a greater spatial and temporal coverage of observations; (2) the ease and speed in communication, recruitment and internal organization between experts and volunteers. Based on these points, experts should rely on user-friendly digital technologies, widely used in everyday practices of citizens, such as smartphones and tablets. However, experts should provide a training phase for the correct use of digital technologies, appropriate to research objectives. The creation of graphical interfaces is also an important aspect to improve the user experience, facilitating interactions between participants through digital platforms for sharing and displaying data. The development of digital platforms for displaying data and results is not a secondary aspect, but an effective tool to increase the participation and sense of belonging of volunteers to the citizen scientists' community. In this way, volunteers become aware of their actions and the importance of their role in a collective problem-solving effort in scientific research.

Prescriptions, here illustrated, refer to a general context of application of citizen science. Based on these prescriptions, it is possible to design scenarios based on the schematization of citizen science reported in Section 2.3.1. Contributory, collaborated and co-created typologies can represent ideal-types for the definition of standard protocols, applicable and replicable to a different empirical cases study. From a contributory perspective, researchers and experts conduct all phases of the research. This implies that the adoption of citizen science as a research method is functional to solving a scientific gap. The role of volunteers is limited to the guided collection of data for the purpose of consulting and refining the research phases. Roles and tasks are predominantly homogeneous, with no distinction of expertise or background among volunteers. The social function of research questions may be secondary in such a context. The development of digital technologies is functional to the guided data collection activity to support the subsequent processing by experts who independently take care of the publishing and dissemination phases. The engagement of online communities is limited to the sharing of data mainly aimed at the collection of a large number of observations in the form of digital contribution.

Collaborated and co-created ideal-types indicate a more active involvement of volunteers in the implementation of citizen science processes. In the first case, the volunteers redefine the research activities set by the experts; in the second they act as peers with the experts. In this context, the definition of research questions assumes social importance, intercepting scientific gaps with needs expressed by communities, both local and virtual. Volunteers not only collect data, but define together with experts the methods and purposes of collection, in order to identify scientifically based responses to social and environmental problems. The definition of tasks and roles within the organization becomes more complex, as it must take into account the inhomogeneities among volunteers in terms of expertise, skills, motivations, interests and personal experience. At the organizational level, the structures of the communities involved become more articulated. Researchers maintain a shared coordination role with advanced volunteers who lead and educate a base of generic volunteers predominantly engaged in data collection activities. In this context, volunteers can increase their conceptual knowledge and technical skills, changing their status within the community. Such ideal types imply changes not only in organizational, but also in behavioral terms, because volunteers and experts can contribute to the achievement of research goals through cooperation. It implies changing in individual behaviors because participants need to synchronize their actions in order to create a group identity.

In a co-created perspective, participants are frequently involved in collective actions. It requires that participants act as a single entity in achieving a specific goal. Decisions are binding and individual behaviors must reflect a general attitude. Participants not only share information and awareness, but also responsibility for their actions.

Contractual and collegial citizen science typologies offer, instead, experimental elements with more uncertain outcomes. Firstly, the role of the experts appears to be limited only to the final review phase. The coordination of research activities is carried out almost exclusively by volunteers. In this context, organizational and technological aspects are difficult to place in a specific and functional structure because of the experimental nature of these approaches.

The aim of this chapter was reviewing main concepts, methods, tools and issues on the application of citizen science to lay the foundation for a theoretical framework across environmental disciplines, social and organization studies. In this sense, theoretical analysis through a systematic meta-review of literature has allowed to examine the multi-faceted and transdisciplinary aspects related to citizen science. In addition to reviewing concepts, methods and tools, the analysis shed light on the possibilities that citizen science offers knowledge on co-production and problem-solving processes based on participatory approaches. However, theoretical analysis also presented the limits of this approach both from an organizational and behavioral perspective and from a technological perspective. At the base of these limits, there are mainly cognitive biases of participants, technological deficiencies, inadequate training, a lack of expertise and experience. This chapter, therefore, identifies pillars on which to design a theoretical framework of citizen science, valid for the management of participatory approaches and changes within organizations. These pillars can be summarized as: (1) definition of a research question that intercepts collective needs to provide scientific valid solutions to social, environmental and economic concerns; (2) identification of target groups active in a specific context; (3) analysis of behaviors of the volunteers and the motivations underlying their participation to assign roles and tasks appropriate to the level of expertise and training of individuals; (4) definition of standard protocols agreed between experts and volunteers to manage the research steps; (5) continuous interaction between experts and volunteers for the sharing of results and the implementation of any corrective measures in scientific co-production processes. Advances in digital technologies and in social media platforms are redefining methods and spaces for interaction and participation, expanding recruitment and engagement of volunteers in the context of online communities. These aspects offer ideas for further research on the topic of citizen science in relation to the changes and challenges posed by digital transformation. The conclusion reported here must be considered as a reflection on the sidelines of a theoretical review on the topic of citizen science. In this study, no empirical cases study was examined or conducted for the validation of statements. The lack of empirical validation represents a limitation of this study. In this sense, this contribution is limited to presenting a transdisciplinary theoretical conceptualization of citizen science as a starting point for the integration of methods and tools of environmental sciences in an analytical perspective linked to social sciences and organization studies.

3. Engagement of online communities within a citizen science framework: insights from hydrology and environmental monitoring

3.1 Introduction

Citizen science is a set of methodological approaches aimed at increasing public participation in scientific research activities through the co-production of knowledge and useful tools for data collection, data processing and dissemination of results (Spasiano et al., 2021). Its main fields of application concerns environmental sciences, earth observation and urban planning, by introducing human and socio-cultural perspectives into technical and scientific tasks. In this way, citizen science support expert researchers in the definition of practical solutions that intercept research questions with social needs (Spasiano et al., 2021; Buytaert et al., 2014; Assumpção et al., 2018; Grace-McCaskey et al., 2019; Jordan et al., 2019). Citizen Science involves the use of crowdsourcing models and participative approaches for the sharing of ideas, the development of projects and the organization of volunteers in research projects (Fienen & Lowry, 2012).

New developments in Information and Communication Technologies (ICT), remote sensing and data processing pave the way to new crowdsourcing activities for social engagement, volunteers' recruitment and organization (Kankanamge et al., 2019; Modaresnezhad et al., 2020). In particular, social media systems allow rapid sharing of information at low cost (de Albuquerque et al., 2015) connecting and organizing people within active communities (Modaresnezhad et al., 2020; Shirky, 2008). Citizen Science can constitute an innovative theoretical framework within which online communities can be engaged for production of new forms of knowledge and for giving innovative perspective in organizational processes. Citizen science, firstly, encourages dialogue and the exchange of information between citizens and experts, in order to increase awareness on public interest issues and in decision-making processes (Spasiano et al., 2021; Buytaert et al., 2014; Hollow et al., 2015; Brouwer et al., 2018). Dialogue and information exchange are also functional to collaborative modelling of tools and processes (Voinov et al., 2016; Basco-Carrera et al., 2017). Volunteers' engagement and participation in a citizen science framework is not limited to data collection only but extends to the shared definition of research problems and the co-production of results for understanding the phenomena (Spasiano et al., 2021; Miller-Rushing et al., 2012).

Despite the developments and integration of ICT and new recruitment methods through social media systems in participatory approaches to scientific research and environmental monitoring, the engagement of online communities in citizen science activities constitutes a research gap. This gap is found both at theoretical and empirical level, where citizen science initiatives are generally conducted on field activities coordinated by experts. The use of ICT and digital technologies, in this context, is usually supportive. Yet, the role of online networks and digital communication tools is increasingly pervasive in the information gathering and exchange between people aimed at knowledge co-production through cooperation and organized collective action (Shirky, 2008).

Starting from this gap, the aim of the chapter is to provide a conceptual framework for the integration of online communities as part of citizen science projects integrating insights deriving from its application for hydrology and water resources management (Assumpção et al., 2018; Nardi et al., 2022). The research method adopted is a theoretical literature review on the concept of citizen science and its implications related to engagement of online communities. Finally, this contribution presents three illustrative cases from hydrology and water resources management to contextualize practical and organizational issues in citizen science projects to hypothesize possible scenarios for the engagement of online communities. Starting from Shirky's (2008) indications regarding the organizational issues posed by online networks and digital communication tools, this contribution tends to outline possible potential scenarios of online communities' engagement in a citizen science framework aimed at co-production of knowledge through information sharing, cooperation and collective action between users. The chapter is structured as follows: section 3.2 is focused on theoretical concepts related to citizen science and explain ideal typical users' attitudes within an online network. Section 3.3 illustrates the research gap in investigating the role of online communities in a citizen science framework. Section 3.4 and 3.5 are focused on insights derived from application of citizen science principles in hydrology and water resources management from theoretical contributions and practical applications. Then, section 3.6 will provide final considerations focused on possible organizational scenarios for enhancing the role of online users in a collective action towards achievement of social and environmental goals, by application of citizen science principles.

3.2 Theoretical framework

A common and statutory definition of citizen science is still missing (MacPhail & Colla, 2020) and its application in research tasks usually reflects empirical concerns. Definition of methodologies, protocols and research methods is the result of dialogue and shared points of view between experts and engaged volunteers (Buytaert et al., 2014; Le Coz et al., 2016). Citizen science aims to promote peer collaboration between experts and citizens, even if the first group often leads research projects because of its level of expertise on scientific topic (Spasiano et al., 2021). In fact, experts refer to professional researchers involved in academic context. While volunteers represent a heterogeneous group, within which individuals can differentiate themselves by level of education, cultural and social background, professional expertise, motivations and interests (Voinov et al., 2016; Kühl et al., 2020).

Furthermore, volunteers can represent different interests or social groups. Expert researchers often engage generic volunteers through call to action or crowdsourcing techniques (Kankanamge et al., 2019; Minet et al., 2017; Zheng et al., 2018). In other cases, volunteers' engagement aims at representatives of local communities, bearers of social and territorial needs, such as bottom-up associations, neighborhood committees or ethnic and linguistic minorities (Buytaert et al., 2014).

These aspects are crucial for achieving common research objectives, defining shared research design, adopting, and implementing suitable tools for data collection and processing aimed at the co-production of knowledge and scientific activity. Starting from these theoretical assumptions, citizen science is usually structured in (1) contributory, (2) collaborated, and (3) co-created typologies according to the level of engagement and tasks assigned to volunteers (Bonney et al., 2009; Gray et al., 2017; Strasser et al., 2019). This tripartition can represent ideal types on which to set up participation strategies. From a contributory perspective, experts maintain their leading role, controlling all stages of the research process. The role of volunteers is limited to the collection and sharing of data useful for research purposes (Bonney et al., 2009; Gray et al., 2017; Newman et al., 2011). From a collaborated perspective, volunteers' engagement includes refining tasks of research question, activities and roles set by experts (Bonney et al., 2009; Gray et al., 2017; Newman et al., 2011). Participants act in cooperation with experts in order to give them insights to analyze under scientific lens. Finally, co-created typologies constitute the highest level of citizen science, in which co-production between experts and volunteers is more evident. Co-created citizen science implies participants' engagement in all stages of research process (Bonney et al., 2009; Gray et al., 2017; Newman et al., 2011). Volunteers' participation is expressed in a call to action in which participants act as peers with experts (Laut et al., 2017).

Based on this ideal-typical tripartition, an organization involved in citizen science activities has a complex and circular structure (Figure 3.1). The complexity derives from the coexistence and co-participation of different types of actors, coordinated by experts. Circularity depends on constant dialogue between actors that interact as peers. Circularity guarantees a constant flow of information between participants at the basis of feedback actions and in support of collective actions within the processes of knowledge co-production, co-management of public and scarce resources (such as water, land, woodlands and food systems), co-assessment of related risks (floodplains, rainfalls, drought, soil erosion) supporting for concerted and shared decision-making processes.

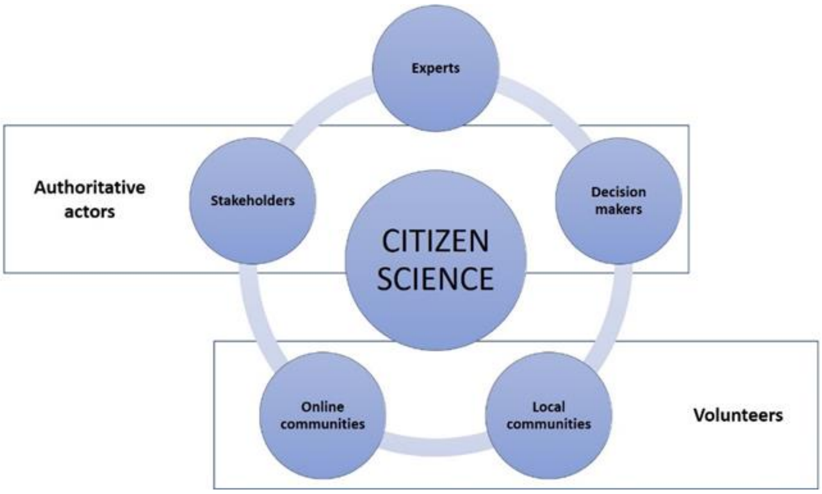


Figure 3.1. Cyclic configuration of citizen science participation (Source: author).

Advances in Information and Communication Technologies (ICT) and digital technologies open new scenarios of knowledge co-production by expanding research tools and methods to social media (de Albuquerque et al., 2015; Le Coz et al., 2016; Braccini et al., 2018). In this context, online communities come into play as a new actor for the co-production of information and data useful for knowledge, innovation and creative solutions (Faraj et al., 2011; Hutter et al., 2011) for organizations enrolled in scientific research (Nardi et al., 2022). The engagement of online communities, thus, transfers the participatory modalities of citizen science within digital platforms in which volunteers can share data and information, organize themselves and take collective actions (Preece, 2000; Braccini et al., 2019). Virtual platforms to share creative ideas to organizations and also to interact between users and experts, building social networks and establishing a sense of community (Hutter et al., 2011). Online technologies support unformal communities in organizing tasks for common efforts (Preece, 2000; Braccini et al., 2019; Ma & Agarwal, 2007). According to Shirky (2008), online interactions among users differentiate in three kinds of effort: sharing, cooperation and collective actions (Shirky, 2008).

Sharing represents the simplest way to interact within an online community or to take advantages from social media tools (Shirky, 2008). Participants' behaviors are similar to contributory citizen science because their tasks are limited to data or information sharing

(Miller-Rushing et al., 2012; Bonney et al., 2009; Green et al., 2020). Cooperation represents a second intermediate level of engagement in an online community. It implies changing in individual behaviors because participants need to synchronize their actions in order to create a group identity (Shirky, 2008; Braccini et al., 2018). Cooperation presents strong similarities with collaborated citizen science because it stimulates dialogue and conversation between participants around issues that defines research question and design, opening new way of knowledge and tools co-production (Miller-Rushing et al., 2012; Bonney et al., 2009; Green et al., 2020). Collective action is the highest level of engagement in an online community. It requires that participants act as a single entity in achieving a specific goal (Shirky, 2008). Decisions are binding and individual behaviors must reflect a general attitude (Shirky, 2008). Participants not only share information and awareness but also responsibility for their action. Collective action is the base of co-production. In this way, it can pose at the base of co-created citizen science because group actions define research scope, methodologies and tools to adopt (Miller-Rushing et al., 2012; Bonney et al., 2009; Green et al., 2020).

These similarities, therefore, lay the foundations on which to set framework models to conceptualize the engagement of online communities in a citizen science framework bringing insights from theoretical and practical application in hydrology and water resources management as an application field of knowledge co-production, as summarized in Figure 3.2.

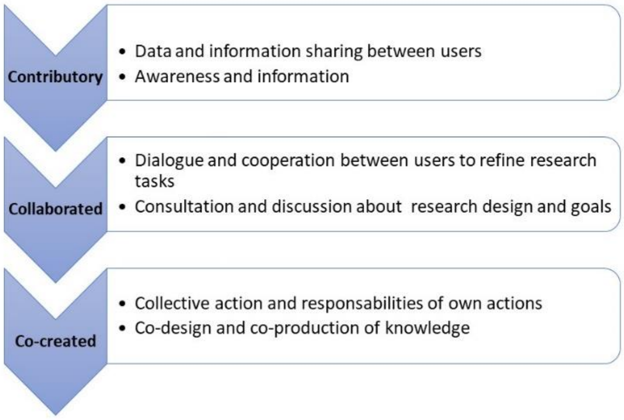


Figure 3.2. Summary of main synergies between citizen science ideal types and online communities' attitudes, according to Shirky's tripartition (2008) (source: author).

3.3 Research gap

Despite the growing pervasiveness of digital technologies in hydrogeological research and ecosystem management that leverage Volunteered Geographic Information (VGI) (Goodchild, 2007) and User-generated contents (UGC), there is a gap with the application of citizen science methodologies with the involvement of online communities. User-generated content data collection usually follows the application of crowdsourcing principles (Zheng et al., 2018; Weeser et al., 2018) and the involvement of volunteers at a first level of data sharing under the supervision of experts or according to involuntary and anonymous data sharing methods (Assumpção et al., 2018; Fienen & Lowry, 2012; Zheng et al., 2018). In recent years, however, there have been several attempts to create active communities as part of citizen science-based research activities (Laut et al., 2017; Aristeidou et al., 2021). Studies on this topic focus not only on identifying profiles of participants (Aristeidou et al., 2021; Aristeidou et al., 2020) but also seek to investigate the knowledge acquired by volunteers and the level of awareness on the issues addressed (Phillips et al., 2019; Geoghegan et al., 2016; Aristeidou et al., 2020). Research on the latter aspect puts volunteers in a perspective of greater interaction between themselves and with experts in the definition of research projects and evaluation of results (Aristeidou et al., 2020; Masters et al., 2016). Investigating acquired knowledge and awareness projects volunteers towards the development of skills is useful to undertake collective actions and intervene on all phases of the research process with the support of experts (Aristeidou et al., 2020). The development of digital platforms therefore allows to contextualize the actions of the participants in a virtual context, often different from the field surveys (Aristeidou et al., 2020).

Investigating on application of citizen science in hydrological science and water resources management provides several insights to develop a conceptualization of the engagement of volunteers in scientific research processes and in organizational issues related to participatory approaches supported by digital tools and social media contribution. Practical applications in hydrological research and monitoring provide terms of comparison and cases-studies to engage online communities in co-production of shared knowledge, co-design of monitoring tools and in promotion of collective action based on users and online communities' contributions enhanced by means of digital platforms and social media contents. Practical applications from hydrology and water resources management give conceptual and theoretical insights to reduce gap in the enhancement of online communities' contributions into citizen science.

3.4 Insights from citizen science in hydrology and water resources management

The application of citizen science offers to the hydrologists and water management scientists new research skills for implementing analytical models through the integration of traditional data collection methods with information provided by volunteer citizens, using their own personal mobile devices (Assumpção et al., 2018; Zheng et al., 2018; Weeser et al., 2018; Lisjak et al., 2017). The advantage offered by personal mobile devices is the ability to offer a continuous flow of data, constantly updated and with widespread geospatial coverage, at low cost (Buytaert et al., 2014; Weeser et al., 2018; Mazzoleni et al., 2017).

Studies on citizen science in hydrology and environmental sciences is mainly focused on the development of organizational and participatory models for the collection and integration of crowdsourced data (Basco-Carrera et al., 2017; Le Coz et al., 2016; Njue et al., 2019). These models are usually based on stakeholders' participation and cooperation in terms of increasing participation of general public, reducing social conflicts, building consensus and promoting negotiation between participants and experts on topics of common interests such as management and sustainable uses of water resources (Basco-Carrera et al., 2017) or risk and flood hazards communication (Le Coz et al., 2016). The adoption of computer-based models – by means of software platforms, suitable smartphone applications for technical data collecting and processing and communication tools – is functional to (1) support communication efforts directed to general public or specific community groups and to (2) analyze social networks patterns in order to identify potential stakeholders to involve, defining roles and tasks within the organization (Reed et al., 2009; Ruzol et al., 2017; Uddin, 2017). Social network pattern analysis allows not only a mapping of organized groups of online users but also to investigate interactions between members of an online community (Williamson & Ruming, 2016) and between users and their context of interaction (Huang et al., 2017; Bojovic & Giupponi, 2020). Context of interaction is composed not only by peer volunteers but also by stakeholders and institutional actors, such as local authorities and research centers that conduct and coordinate scientific activities or commission research based on co-production of knowledge and co-design of tasks and goals (Reed et al., 2009). Introduction of social media tools in citizen science investigation is reshaping socio-spatial networks of participation, projecting the engagement of volunteers from community-based approaches towards virtual contexts (Reed, 2020).

Some peculiar factors stem from literature review supporting engagement and organizational processes in the application of citizen science in hydrology, both in physical and virtual context. These factors can be summarized in (1) the simplicity of the procedures adopted in the engagement of volunteers through simple instruction to carry out (Le Coz et al., 2016); (2) development of suitable tools for data collection and processing – such as, smartphone applications or surveys by means of social media – functional to perform technical tasks in an intuitive and immediate way (Le Coz et al., 2016); (3) development of communication strategies aimed at organizing users and optimizing communications and information exchange between participants (Le Coz et al., 2016; Reed, 2020); (4) stakeholders' analysis to assign roles and tasks within the organization and define levels of participation and collaboration (Basco-Carrera et al., 2017).

User participation is an interactive and iterative process that involves different types of volunteers depending on the level of education, expertise, motivations and interests (Basco-Carrera et al., 2017; Kühl et al., 2020). These aspects are strategic factors for durability of citizen science projects and the organizational structure of a cohesive and active community (Buytaert et al., 2014; See et al., 2016; Lee et al., 2018). Stakeholder's analysis determines the level of engagement of volunteers within an organization. Their engagement includes different level from participation in terms of information, awareness and consultation to active collaboration in public discussion for definition of research design, co-production of knowledge and co-decision making (Basco-Carrera et al., 2017). Motivations and interests can vary from personal interest to gaining power within a community by means of knowledge (Bonney et al., 2009); from improving social relationship to social learning (Buytaert et al., 2014; Voinov et al., 2016); from promotion of joint action to civic participation in co-management of common resources, such as water or agricultural services (Villaseñor et al., 2016). From a technological perspective, keeping high motivation relies on development of dashboard of data visualization and digital interactive tools to make user aware on volunteered contribution in research activity. Frequently call to action and feedbacks by email can enhance user's role within online communities, making them feel part of a group (Buytaert et al., 2014; Voinov et al., 2016).

Several studies investigate on novel tools offered by the use of digital technologies and the role of social media in gathering data and information for implementing hydrological and water resource management models (Le Coz et al., 2016; Zheng et al., 2018; Etter et al., 2020; Strobl et al., 2020), monitoring flood risk and disaster risk reduction (Kankanamge et al., 2019; de Albuquerque et al., 2015), measuring streams flow and water levels (Etter et al., 2020; Strobl et al., 2020). Expert researchers assimilate information observed by users for the implementation of hydraulic models based on time-series and large geospatial coverage of contributions (Annis & Nardi, 2019). However, many applications of this kind rely on crowdsourcing activities that are often involuntary, where the production of data is not the result of deliberate actions within a citizen science research purpose (Kankanamge et al., 2019; Njue et al., 2019). This issue often occurs in cases where contributions are derived from social media contents, where users are not directly involved or engaged in scientific activities (Njue et al., 2019). The illustrative cases in the next paragraph show how the development of digital and web-based platforms is functional not only to offer technological solution to data collection but also to the construction and enhancement of online communities engaged in water resources management and hydrology under supervision and coordination of experts.

3.5 Digital platforms for engaging communities in hydrology and environmental monitoring

Several citizen science initiatives on community-based approaches focus mainly on the topic of water management with particular attention to atmospheric phenomena that affect the water cycle and water quality intended as an essential ecosystem service for functioning and social well-being (Buytaert et al., 2014; Weeser et al., 2018). In this sense, such initiatives tend to create active communities around water management and monitoring through the development and implementation of digital platforms and the use of suitable and ready-to-use apps. The development of online platforms is part of citizen science's progress towards new conceptual, technological and communicative paradigms aimed at widening interactions between users in a common and shared effort (Disney et al., 2017).

Spotteron, CitSci.org and AnecData represent three illustrative cases that exemplify the application of citizen science in environmental research and monitoring through engagement and enhancement of online communities. The purpose of these platforms is not only to collect data, but also to create operating communities that can constantly share and update personal and collective opinions and experiences in relation to topics of scientific interest, highlighting their impacts on daily experiences. The Spotteron platform offers, for example, advanced digital tools (such as digital maps) for the collection and mapping of information by citizens on various topics of scientific interest. As part of hydrology and water management Spotteron has developed the CrowdWater app (Seibert et al., 2019) in order to collect information on water level and estimate water flows (Seibert et al., 2019). The application has been used in several studies since the estimation of flows (Etter et al., 2020; Strobl et al., 2020) to monitor microplastic pollution of waterways (Van Emmerik & Schwarz, 2020). The involvement of citizens takes place through training and gaming phases in order to build a community attentive, educated and sensitive to the purposes of research and above all to keep the motivations of citizens within the community high through rating and ranking systems of the information received (Strobl et al., 2020; Strobl et al., 2019). Through the training and gaming system, the researchers wanted to set up the construction of a community attentive to water management issues in order to obtain active citizens as sensors on a specific geospatial context to provide data and at the same time improve their perception of water resources and the risks related to them for greater sensitivity in terms of water use and consumption.

CitSci.org platform supports collaboration between researchers and citizen scientists in research and decision-making activities (Wang et al., 2015). Users can freely access to the platform defining research questions, shared issues and scenarios, developing shared research plans and activities with a view to promoting online collective action initiatives (Gray et al., 2017; Wang et al., 2015). Users can also build models, collect data and view results according to a shared participatory model in order to create inclusive and participatory management protocols (Gray et al., 2017).

The AnecData platform provides tools for crowded data collection and interpretation towards the solution of common issues addressed within Citizen Science (Disney et al., 2017; Bailey et al., 2021). Available tools include datasheets, image uploads, charts, and data mappings (Disney et al., 2017; Bailey et al., 2021). Communication tools underpin the potential to create cohesive and active communities through online channels (Disney et al., 2017; Bailey et al., 2021). The platform supports collective actions aimed at solutions to collective problems by creating networks between experts and citizens. Its function is not only limited to the production of knowledge but also to promoting class actions (Disney et al., 2017; Bailey et al., 2021).

Digital platforms – like those illustrated above – provide technological support to citizen science projects with a wide range of features and advanced tools. Social community extensions – such as newsfeeds, forum, comments, liking and user following, data visualization and summary – constitute many advanced functionalities that facilitate interactions and information exchange at the base of communication strategies, community building processes and new forms of distributed collaboration (https://www.spotteron.net/apps, last accessed 2021/08/24; https://www.citsci.org, last accessed 2021/08/24). The scope of citizen science platforms is to generate measurable results for scientific research and evidence-based decisions. Data quality extensions offer tools for analyzing and validating citizen observation and for reducing errors and biases.

3.6 Final considerations on online communities' engagement in hydrological monitoring

In this contribution, authors have examined the main characteristics of citizen science as a theoretical framework for the engagement of online communities in the processes of scientific knowledge co-production in support of innovative and shared solution for water and hydrological resource management and assessment. Authors have, therefore, examined three illustrative cases aimed not only at investigating the technological aspects, but above all at focusing on the methods of creating communities in order to identify essential and peculiar characteristics that can integrate online communities in a citizen science framework. Finally, the contribution aims to provide insights for the engagement of an online community to support citizen science initiatives across a transdisciplinary application between social and hydrological sciences with the support of digital and information systems.

The role and potential of online communities in a citizen science framework is currently still little explored.

The theoretical insights and practical examples shown in this contribution offer general guiding principles for setting up the organization of online communities in a participatory scientific research process. Digital platforms, such as Spotteron and CitSci.org, offer interesting digital solution to be replicated in several study contexts for the construction of active communities around environmental issues to support scientific research and decision-making processes. These platforms constitute not only a digital solution for a large-scale data collection, but also lay the foundations for the construction of communities engaged in the monitoring and management of socio-environmental processes. In some cases, the team of researchers experimented with the use of dashboards and gaming for long-term engagements of participants and to evaluate the effectiveness of volunteered observations. These solutions can constitute long-term monitoring tools to verify and quantify the contribution provided by volunteers not only in terms of data provided but also for measuring validity, effectiveness and temporal continuity.

Online communities can broaden the recruitment area of volunteers with the support of digital technologies and social media. Digital solutions facilitate communication within the organization offering the ideal medium to involve non-expert volunteers using user-friendly and intuitive tools. Citizen science provides the theoretical framework on which experts can set up participatory research works and develop participatory processes aimed at the co-production of scientific contents not only and not so much to solve academic research questions, but above all to find concerted solutions to contemporary challenges, such as consequences of climate change or assessment of scarce resources.

In this context, social media (1) implies the adoption of new data collection methods; (2) offer new tools for communication and rapid online interaction between experts, stakeholders and citizens; (3) they constitute investigation tools to identify attitudes and behavioral patterns at the basis of the organizational structures of groups of volunteers.

In the light of the examination of the literature and illustrative case reported, three possible scenarios for integrating online communities into citizen science framework can be outlined. The first scenario is of a collaborative type, in which users contribute to the co-production of knowledge by sharing data deriving from direct observation of phenomena. In this context, users act as widespread human sensors, autonomous in their action with a low level of interaction. The second scenario is cooperative, in which users' actions are synchronized within an organizational structure coordinated by experts. In this context, data collection activities and interactions among users are guided according to specific goals fixed by experts. The third scenario is collective. It represents the highest level of integration of online communities into citizen science processes. In this scenario, the community building is completed. Users share common values and visions at the base of joint action with experts.

Citizen science initiatives in hydrology and water resources management are usually based on community-based approaches and crowdsourcing activities. Community-based approaches do not necessarily imply the use of digital and web-based technologies and crowdsourcing activities are often unintentional and not specifically aimed at full engagement of volunteers in scientific research processes. Engagement of online communities in citizen science would make systematic data collection in a context of continuous and active monitoring aimed at intercepting collective social and environmental needs and directed towards concerted solutions to problems related to urban planning and environmental management. Another peculiarity is the virtual interaction of online communities. This aspect allows the replicability of organizational and communication models on different geographic large-scale application contexts and case studies, not only limited to assessment of environmental and water resources but also extended to other fields such as public sector accounting, assessment of public services (transportation, health, education), ecosystem and agro-food systems assessment, co-management of network services and infrastructures.

Despite the wide availability of publications, application cases, tools, techniques and digital platforms related to citizen science, the impacts of this approach at the level of human behavior and cultural change represent a field of investigation that is still little explored and in an experimental phase. Further studies on the topic will have to be directed to shed light on the ability of citizen science to create cohesive and organized communities and on behavioral changes both individually and collectively. The study of these aspects will be able to shed more light on the motivations and interests underlying the involvement of citizens in the production of scientific knowledge and in decision-making processes. Aspects that complement and integrate with the collection of data and observations and their validation through the implementation of traditional analysis models.

Part II: Cases-study

4. Citizen as interpreter: testing principles of citizen science in the estimation of stream water level through photo-traps frame

4.1 Introduction

Monitoring intermittent and ephemeral streams is a significant challenge in hydrology in terms of collecting accurate and continuous data at different spatial and time scales (Davids et al., 2017; Strobl et al., 2020; Noto et al., 2022). Difficult-to-access-environments and unstable riverbed conditions represent a significant portion of upstream areas hindering continuous and accurate hydrologic data acquisition using traditional instruments, such as remote sensing and river gauging stations (Van Meerveld et al., 2017; Seibert et al., 2019; Noto et al., 2022).

The use of low-cost tools, supported by citizen science and crowdsourcing methods, represents an innovative and effective hydrologic monitoring solution for such challenging domains and scales (Weeser et al., 2018; Zheng et al., 2018). The use of participatory methodologies is recognized as an important technique for next-generation solutions, also considering the value of increased engagement and awareness of indigenous communities. These methods are recognized to be fundamental to potentially address the 23 Unresolved Problems in Hydrology (UPH). UPH – an effort by 230 research scientists sharing the view and plan to project hydrology research efforts into the future – recognized transdisciplinary engagement as an important method to tackle technological, social, cultural, and organizational challenges affecting hydrologic research (Blöschl et al., 2019; Nardi et al., 2022).

Among the UPH, Blöschl et al. (2019) poses two major concerns regarding hydrological measurements and data collection: (1) the adoption of innovative technologies to measure and estimate surface water flows at different spatial and time scales (UPH #16); and (2) the collection of soft data from volunteered observations and their integration with traditional hydrological observations (UPH #17). Other issues focused on synergies and trade-offs between various societal goals in water management (UPH #22).

Crowdsourcing requires the use of suitable technologies to engage non-expert volunteers to carry out empirical research activities – such as data collection and interpretation – and higher-level work such as the co-production of knowledge and dissemination of results (Spasiano et al., 2021). Considering the multidisciplinary perspective of this type of work, the use of citizen science requires standardized and controlled protocols to support the validity and reliability of the results (Kosmala et al., 2016; Cappa et al., 2016).

UPH, with specific focus on the complexity of human-water interactions, prompts the need for adoption of transdisciplinary methodological approaches for solving hydrological challenges. In particular, the introduction of soft data (collected through informal methods) for use in estimates and measurement in hydrologic models, can be important for the estimation of water levels or water flows, and for monitoring of water quality in a stream (See et al., 2016; See, 2019; Schrögel & Kolleck, 2019; Zheng et al., 2018; Etter et al., 2020).

Citizen science constitutes a methodological paradigm, within a participatory approach to scientific research, for its characteristics of multidisciplinary and transdisciplinary collaboration (Eitzel et al., 2017; Gray et al., 2017; Knapp et al., 2019). As stated in Spasiano et al. (2021), multidisciplinary collaboration means the application of citizen science which covers several subject areas; while transdisciplinary indicates the integration of different scientific backgrounds and research designs – with operational, professional, and societal perspectives linked in a unique theoretical framework (Spasiano et al., 2021).

In this experimental hydrology research, citizen science offers benefits which address data scarcity through the involvement and active participation of volunteers. By acting as sensors or interpreters, volunteers are an important data source that extends spatially and temporally (Goodchild, 2007; Assumpção et al., 2018). Citizen science also offers social, cultural, and organizational benefits in terms of: (1) *raising awareness*, to encourage sustainable behaviors and a better use of water and environmental resources, with the potential for cultural change of citizens in their relationship and common use and management of water and related risks; (2) *democratization of science*, to promote bottom-up approaches to contextualize scientific research in a local, socio-cultural context; and (3) *knowledge gained and social learning*, towards adaptive forms of environmental management and decision making based on dialogue, consultation, and sharing of knowledge and practices that could be useful to address public issues (Walker et al., 2021).

In recent times, scientific research has investigated the value of citizen and online communities' involvement in environmental monitoring, and methods and tools to obtain large quantities of data to ensure homogeneous spatial and temporal coverage (Bonney et al., 2009; Dickinson et al., 2012; Zheng et al., 2018; Schrögel & Kolleck, 2019; Spasiano et al., 2022). The development of digital technologies makes widely available the use of tools such as smartphones and other applications for the immediate and standardized collection of data (Njue et al., 2019). Njue et al. (2019) classifies data acquisition procedures, in the context of citizen science, as: (1) automated, (2) semi-automated, and (3) manual, which require the use of smartphone applications, digital solutions, or text media.

Methods and tools also differ according to the specific aspects to be investigated, including water levels, flow, and quality. The application of models and tools related to citizen science do not reflect a single standardized procedure but rely on specific empirical applications commonly aimed at widening and increasing the availability of data through the involvement of citizens, especially in contexts where data acquisition is difficult (Assumpção et al., 2018). Also, the engagement methods differ according to the specific contexts and objectives set in the research phase.

Regarding water level estimations, several studies adopt data collection and public engagement approaches through the combination of automated and manual methods (Njue et al., 2019). These approaches aim to obtain water level estimates by volunteer observations which are then compared to benchmark values, official data, or with qualitative methods (Van Meerveld et al., 2017). Some studies have implemented crowdsourcing tools for the acquisition of environmental data through mobile-phone and SMS-text messaging (Lowry & Fienen, 2013; Fienen & Lowry, 2012; Weeser et al., 2018).

These applications combine automated and manual methods of data collection with digital tools at social and cultural levels (Weeser et al., 2018). Advances in digital technology enable data collection and public engagement processes to be implemented through smartphones and user interaction and data sharing platforms.

For example, data collection methods can be used on virtual staff gauge locations in which volunteers, in the role of human sensors, qualitatively estimate water levels by means of specific smart device apps (Seibert et al., 2019; Etter et al., 2020; Strobl et al., 2020; Nardi et al., 2022). These solutions, empowered by advanced digital technologies, can support, not only the citizen data collection activity, but also the organizational and communicative aspects that support the active participation of volunteers in the processes of knowledge sharing and co-production through specific platforms (Spagnoletti et al., 2015; Le Coz et al., 2016).

This work illustrates a pilot case study testing methodological approaches of citizen science in water level estimation of intermittent basins, with the specific goal of validating the image recognition algorithms' calibration by means of crowdsourced automation estimations. This first case study was carried out with the support of researchers from University of Tuscia and Water Resources Research and Documentation Center (WARREDOC).

On a technological level, Noto et al. (2022) designed and developed a stage-camera system for monitoring water levels in ungauged headwater streams by means of an image-based approach. This method was implemented with a simple, white-painted steel pole to estimate water depth as compared to the out-of-water pole segment displayed (Noto et al., 2022). This stage-camera system allows the acquisition of stream images at regular temporal intervals of 20 minutes. The system proved to be adaptable and reliable to understand and monitor the flow variations in headwater streams.

This research, thus, tests volunteer capabilities to provide reliable data for integration into a calibration strategy of the stage-cam method. The proposed procedure uses mean and median positioning, and variability measures, to assess volunteer performance to assign reliable values and to evaluate the effectiveness of volunteer observations over time.

Starting with positioning measures, the study then calculates mean absolute error (MAE) and mean absolute relative error (MARE) as synthetic indices to determine the uncertainties associated to voluntary observations. Qualitative insights from demographics indicators (educational background, university position, and environmental expertise) are also analyzed to evaluate the impact of social and cultural components on volunteers' performance. The proposed test applies principles of citizen science according to a transdisciplinary approach.

The research design is based on citizen science principles in terms of: (1) engagement of a small and controlled group of volunteers; (2) recruitment and training activities; (3) digital communication campaigns to support engagement; and (4) data processing. To conduct this experimental study, we adopted a contributory citizen science approach (Bonney et al., 2009). Our research team organized and coordinated all procedures of the experiment to support the volunteered data collection activity.

This chapter is structured as follows: in Section 4.2, the authors provide an overview of citizen science principles and their application in water science. Section 4.3 focuses on methods and data collection descriptions at the foundation of the research design. Section 4.4 illustrates the results derived from data analysis. Sections 4.5 provide insights from this first-hand citizen science experiment.

4.2 The adopted citizen science framework

4.2.1 A brief summary of citizen science principles

The term citizen science generally refers to the engagement of non-expert volunteers in research activities. Citizen science knowledge and tools are often employed to face environmental challenges, such as the sustainable management of water resources, flood monitoring, and disaster risk reduction (Buytaert et al., 2014; Annis & Nardi, 2019; Annis et al., 2022). Citizen science approaches vary depending on the level of citizen engagement and the roles assigned to volunteers in data collection, processing, dissemination, and interpretation of results (Jordan et al. 2015; Bonney et al., 2016; Phillips et al., 2019).

In a contributory citizen science perspective, crowdsourcing is a basic technique for engaging volunteers in research activities as data collectors or interpreters (Jordan et al., 2015). Advanced citizen science approaches engage volunteers in the phases of consultation on methods and goals (collaborated citizen science) or co-designed and co-production of scientific knowledge (co-created citizen science) (Thornhill et al., 2019; Phillips et al., 2019). These advanced citizen science approaches are applied when research goals match collective social and environmental needs.

Citizen science is an empirical research approach which has a conceptual definition and theoretical framework subject to academic debate (Eitzel et al., 2017). However, the scientific literature identifies general methodologies and procedures that distinguish citizen science as a valid research approach (Njue et al., 2019; Spasiano et al., 2021) that include:

- Adoption of simple procedures
- Development of suitable (digital) tools
- Implementation of communication strategies
- Analysis and assignment to volunteers of specific roles in the research process and knowledge co-production

4.2.2 Integration of soft data and crowdsourcing techniques in water science

The use of soft data, as an alternative and complementary source of data, is a common practice in the field of hydrological-hydraulic modelling – such as in the estimation of water levels. However, data types and acquisition techniques can vary depending on context and purposes.

Soft data can be distinguished as intentional or unintentional (Zheng et al., 2018). The first category includes data collected intentionally for scientific purposes. The volunteer collects data – usually via digital mobile devices – for scientific research and environmental monitoring purposes (See et al. 2016). To this regard, citizen science approaches are adopted for the engagement of volunteers. Unintentional data is a category of data generated for purposes other than scientific research and environmental monitoring.

This is incidental data, often unstructured, including textual information and social media contents (Zheng et al., 2018). Data mining techniques are usually used to extract scientifically relevant information from user-generated contents, without the active involvement of volunteers. Unintentional data also includes data acquired by automatic detection tools which do not require direct and intentional action by human agents (Zheng et al., 2018).

In the field of surface water levels and water quality, the acquisition of data from citizen observations is mainly supported by: (1) dedicated tools; and (2) images or videos (Zheng et al., 2018; See, 2019). Dedicated tools include the development or adoption of technological solutions (software packages, apps, digital platforms) for real-time data collection (See et al., 2016; Zheng et al., 2018; Siebert et al., 2019; Strobl et al., 2020). Images or videos provide data from in-situ instruments and sensors for subsequent analysis by volunteered users (Starkey et al., 2017).

This categorization also reflects a differentiation of activities and roles played by volunteers schematically divided into *citizen as sensor* (Goodchild, 2007; Elwood et al., 2012; Nardi et al., 2022) or *citizen as interpreter* (Assumpção et al., 2018). In the first case, volunteers act as sensors for field activities by using mobile digital devices to collect intentional data to be integrated into subsequent analysis and modeling (Le Coz et al., 2016). In the second case, volunteers do not collect data directly but are required to provide interpretations of an event by direct observation, but not necessarily in real time.

The use of soft data in water science is a widespread and well-established practice, notwithstanding some challenges remain. A first order of challenges concerns the ability and reliability of voluntary observations in relation to citizens as data interpreters – how accurate are their observations (Assumpção et al., 2018). Regarding this concern, we designed and tested a procedure of engagement and observation collection, by means of standardized and replicable protocol. The adopted procedure aimed at reducing and quantifying margins of error resulting from subjective evaluations. Standardization, homogenization, and large-scale data collection constitute a second order of problems which must be overcome to confidently use soft data in water science.

4.3 Methodology and data

This section describes the methods and data used in this research. Firstly, we illustrate the research methodology to understand the data collection process from the engagement activities of volunteers. Secondly, we report the adopted empirical approach to our methodology based upon firsthand experience to support our citizen science project.

4.3.1 The hydrological application: stage-cam for water level observation

The stage-cam system represents a low-cost technological solution to acquire images that quantify water level variations in ephemeral streams at regular intervals of time (i.e., 20 minutes). The infrared technology integrated in the stage cam allows the retrieval of images at night and in low visibility conditions, ensuring continuous temporal coverage.

The study area is the Montecalvello Creek Basin in the province of Viterbo (central Italy), about 100 km north of Rome, where 16 stage-cams were installed to monitor the drainage network. With this set up, it was possible to estimate water levels upstream and downstream during the same meteorological event, and also to compare different events at the same site. In front of the camera lens, positioned at the bottom of the watercourse, a white-painted pole was installed to serve as the reference observation tool for estimating stream water levels.

At peak flows, a black ribbon was tied to the pole as a reference point to estimate water levels by an out-of-water-length method (Figure 4.1). Image analysis algorithms, used on the collected white pole images allowed the estimation of the distance in pixels between the black ribbon and the water surface elevation, providing the surface water level at a specific range of time.

Figure 4.1. An example of stage-cam system installed at the Montecalvello basin.

Common hydrologic monitoring instruments are not effective in low-flow surface water environments, typically because a benchmark is not available for the calibration or the validation of data. The use of citizen science volunteers is a promising solution to obtain large data samples from numerous observations of streamflow levels. However, the use of citizen science implies, firstly, the need to identify a potential group of volunteers as field testers to verify the validity of the adopted procedures; secondly, the implementation of simple and replicable procedures for non-expert volunteer groups; thirdly, the use of digital technologies that enable volunteers to join the project, to access information, and to carry out the activities remotely and in a dependable and controlled environment.

Unlike most citizen science projects, in this study our research team asked volunteers to act as interpreters. Volunteers were not required to acquire data from their own but were asked to examine images provided by teams of experts according to established procedures. This solution tended to mitigate the potential margin of error but also limited the role of volunteers as contributors.

4.3.2 Training and engagement methodology of volunteers

The engagement methodology adopted in this project was based on simple procedures illustrated in Figure 4.2. The methodological procedure was articulated as follows: (1) recruitment and training; (2) engagement and digital communication; (3) data collection; and (4) results dissemination.

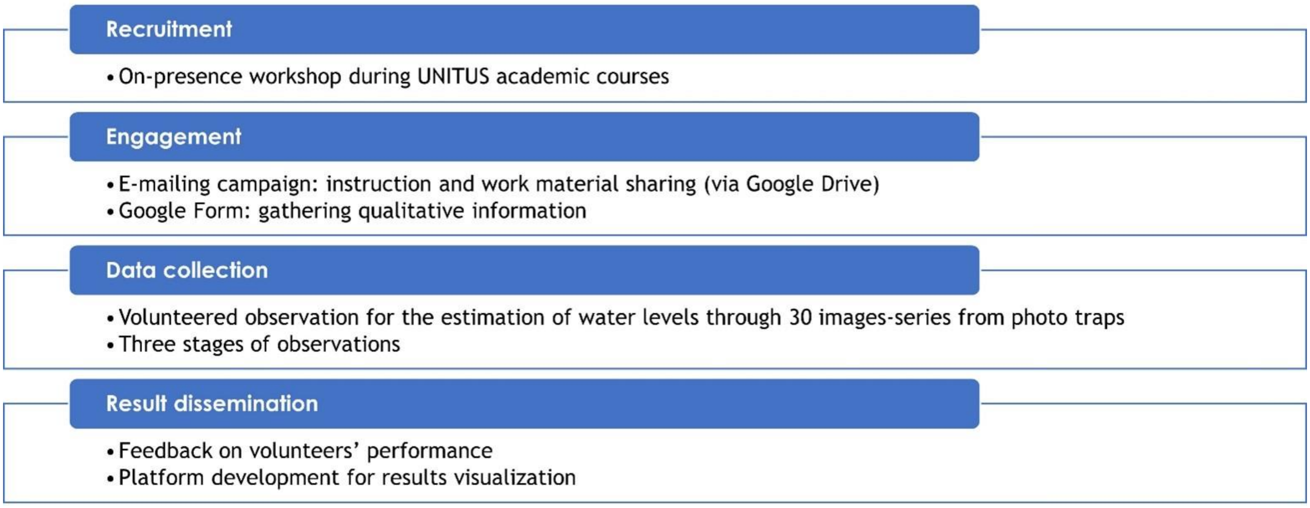


Figure 4.2. Methodological procedures adopted to support active participation of volunteers.

Recruitment activities, designed by the research team, included a dedicated brief workshop to prepare prospective citizen science students. The workshop (1) presented the research project; (2) framed the environmental and social issues related to the monitoring and management of water courses; (3) explained citizen science as a method of research towards shared and participatory solutions for water challenges; and (4) provided training on volunteered activities to estimate stream water levels through the observation of photo-traps frames.

The engagement activity took place during in-person meetings with students of different academic levels and disciplinary backgrounds. The research team organized brief workshops of 30 minutes each during classroom sessions to involve as many students as possible. During in-person workshops, researchers provided a theoretical introduction to citizen science to explain the use of non-expert volunteers in environmental and hydrogeological monitoring.

Researchers also trained students on the required activities for the project, to be carried out remotely. The training phase involved: (1) observation of images through open-source software GIMP; (2) recording observations on a spreadsheet shared in the cloud. The meetings were held over four months - from January to April 2022. At the end of each workshop, the researchers asked participants to provide email addresses in order to: (1) identify and involve in the project only people interested to participate voluntarily; (2) share the material (images to observe and tutorials) to carry out the required activities remotely; (3) share research progress and results; (4) support the project through communication campaigns. The engagement methodology was designed to test and verify the voluntary character of the project. No monetary awards, university credits, nor other types of benefits were provided to students.

The data collection activity consisted of a stage of direct observations aimed at analyzing a sequence of continuous images related to a given upstream basin site. Volunteers were asked to examine sequences of 30 images during a rainfall event. The purpose was to estimate variations in streamflow levels. Subsequent replication observation stages were planned to cross-test the validity of the methodological procedure, volunteers' capabilities, and their interests to the project in the short term.

At the end of observation stage, the results are shared by a dedicated web interface and dashboard which allowed participants to visualize their observed data and project outcomes.

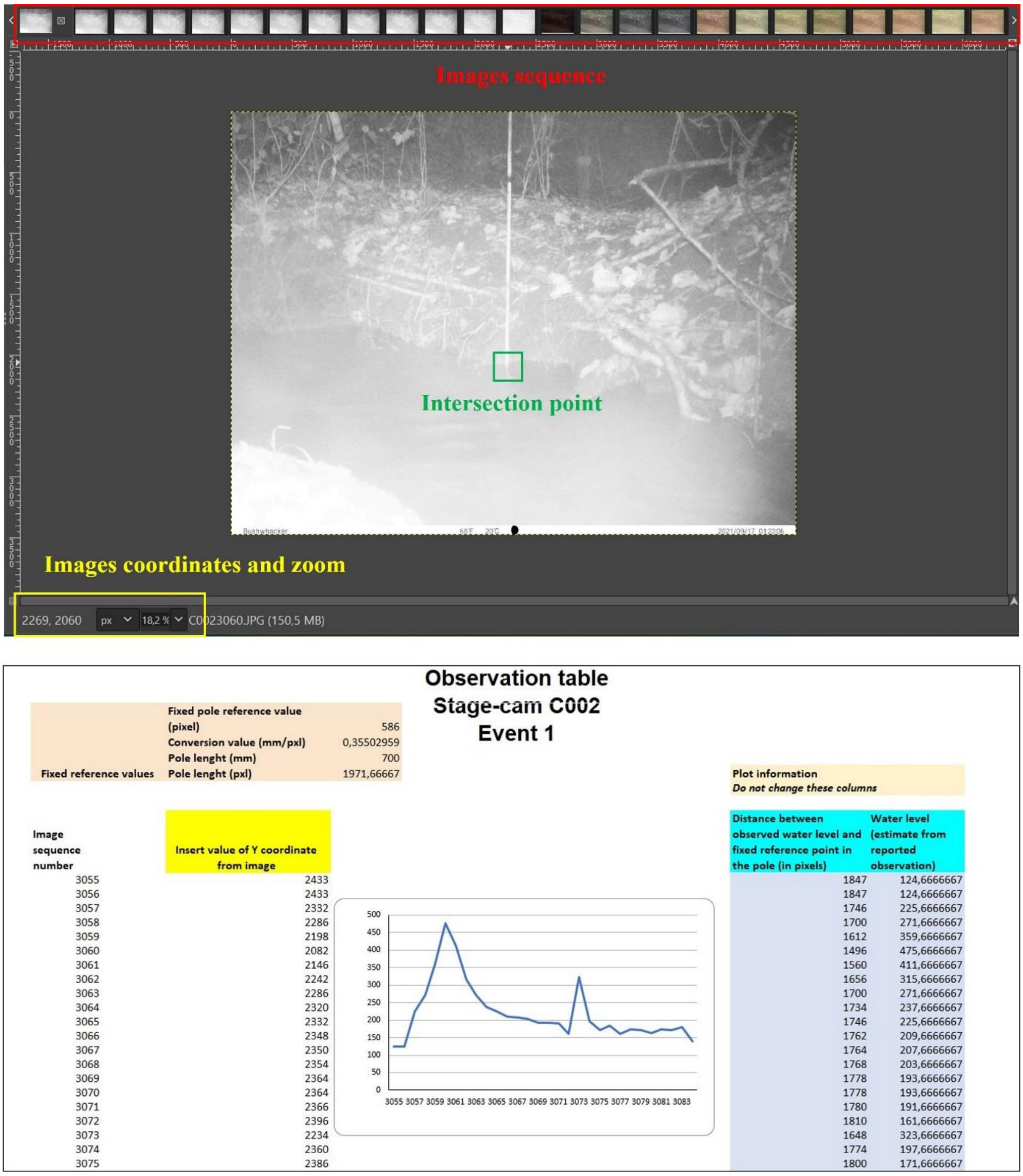
4.3.3 Data

The first-hand experimental test was based exclusively on direct observations of volunteers to assess their reliability by means of positioning, variability measures, and error estimation. Our research team developed a specific and controlled protocol of procedures to guarantee the effectiveness and validity of data collection, and to reduce uncertainty resulting from subjective perceptions. During the in-person workshops, we instructed volunteers on the procedure to acquire controlled data and on how to share it with researchers. In this regard, each volunteer received an online folder with the materials needed to perform the required tasks: (1) subfolders with images to analyze; (2) a table to report observations; and (3) tutorials with guided steps to carry out the tasks.

After visualizing image sequences, volunteers filled a shared spreadsheet to report the value of the coordinate Y – at the point of intersection between the water level and the reference pole – to estimate changes in water levels (Figure 4.3). To derive these water level estimates, absolute reference values were established:

- Fixed pole reference value [pixel]
- Pole length [mm]
- Pole length [pixel]

Then, we derived the difference between the observed water level and the fixed reference point on the pre-installed white pole. This value, subtracted from the length of the observation pole, provided the estimate of water levels for each of the 30 images (Figure 4.3).



Observation table
Stage-cam C002
Event 1

Fixed reference values	Fixed pole reference value (pixel)	586
	Conversion value (mm/pxl)	0,35502959
	Pole lenght (mm)	700
	Pole lenght (pxl)	1971,66667

Plot information
Do not change these columns

Image sequence number	Insert value of Y coordinate from image	Distance between observed water level and fixed reference point in the pole (in pixels)	Water level (estimate from reported observation)
3055	2433	1847	124,6666667
3056	2433	1847	124,6666667
3057	2332	1746	225,6666667
3058	2286	1700	271,6666667
3059	2198	1612	359,6666667
3060	2082	1496	475,6666667
3061	2146	1560	411,6666667
3062	2242	1656	315,6666667
3063	2286	1700	271,6666667
3064	2320	1734	237,6666667
3065	2332	1746	225,6666667
3066	2348	1762	209,6666667
3067	2350	1764	207,6666667
3068	2354	1768	203,6666667
3069	2364	1778	193,6666667
3070	2364	1778	193,6666667
3071	2366	1780	191,6666667
3072	2396	1810	161,6666667
3073	2234	1648	323,6666667
3074	2360	1774	197,6666667
3075	2386	1800	171,6666667

Figure 4.3. Working environment for data collection and observations recording: (upper figure) – A screenshot from GIMP displays the time series of 30 images related to stream water levels (lower figure). The observation table shows values provided from image visualization by volunteers.

4.4 Results

In a recent study, Capdevila et al. (2020) points out how citizens' attributes can constitute potential success factors of improved data quantity and quality utilizing citizen science. These citizen attributes include: (1) knowledge and experience; (2) awareness of environmental issues; and (3) socio-economic backgrounds of citizens (Capdevila et al., 2020). Starting from this theoretical framework scheme, we created a preliminary survey for participants after the initial engagement step. Since this sample was limited to students from the university community, qualitative information collection was focused on: (1) educational level; (2) university career background; and (3) non-academic environmental expertise to relate the data collection activity to specific socio-cultural patterns (Figure 4.4).

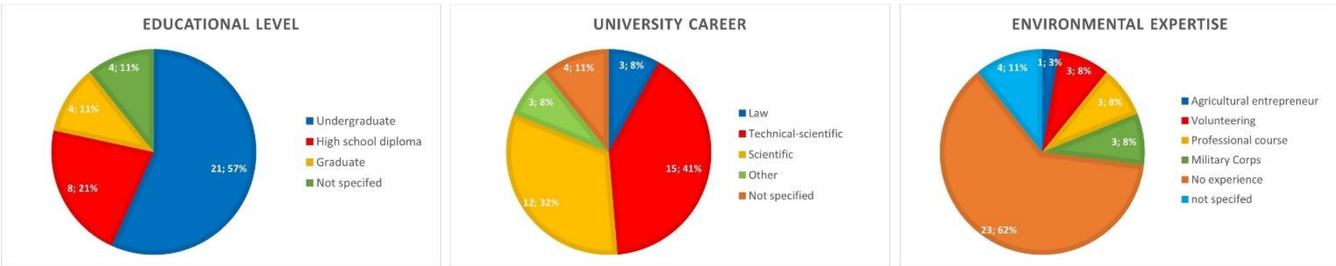


Figure 4.4. Qualitative attributes of volunteers engaged in active participation: (left-panel) educational level; (central panel) university caree path; (right panel) environmental expertise.

Figure 4.4 suggests that the collected sample is quite heterogeneous. Indeed, volunteer academic backgrounds span from humanities to engineering, and from high school to graduate-level programs. Most students did not have any expertise or prior background in similar environmental topics.

4.4.1 Insights from observation stage

We analyzed the observations of 37 student volunteers (our maximum number of active volunteers). Figure 4.5 summarizes the variation of water levels from the collected volunteer observations. The boxplot depicts the confidence intervals and positioning trends for each photo-trap image.

Results indicate a high variability of the student observations, despite a strong concentration around the median values for each analyzed image. To better interpret these trends, we estimated the MAE and the MARE of each student volunteer and compared each observation with a benchmark value. The benchmark value was derived from the observations provided by an expert from our research team. Furthermore, researchers estimated the mean absolute error for each volunteer to see how far each observation deviated from the benchmark value.

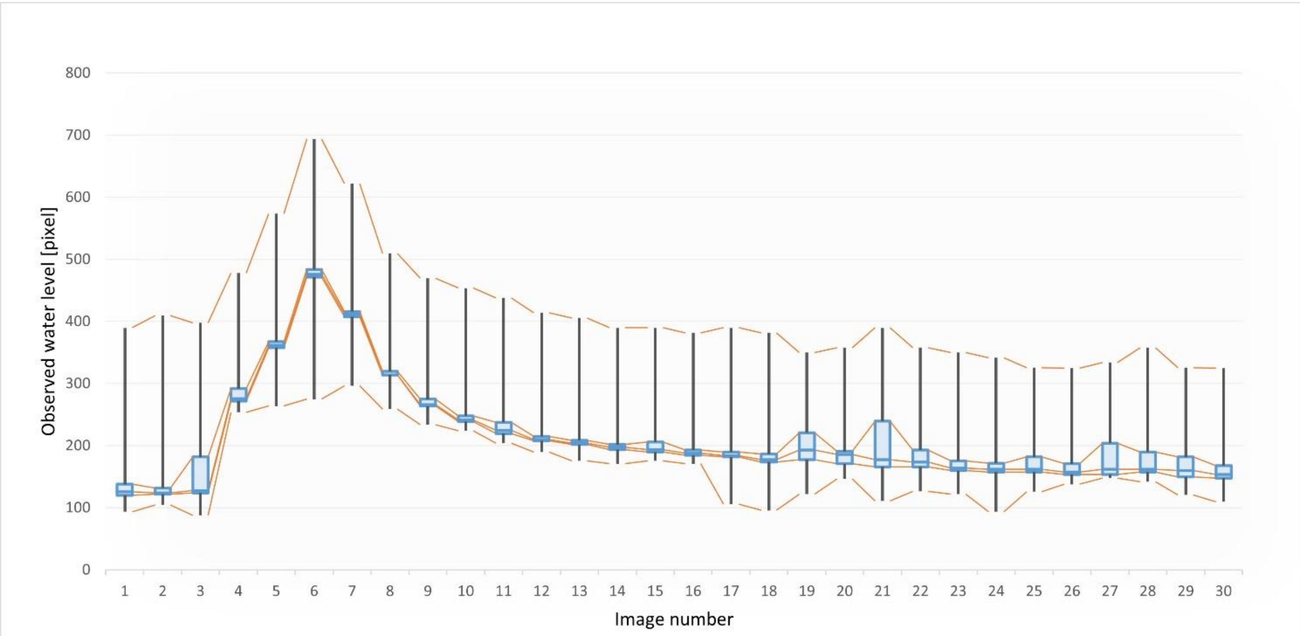


Figure 4.5. Variation of observed water levels at the initial observation stage. A total of 37 student volunteers took part in this stage.

Finally, we estimated the average mean absolute error of all volunteers which was equal to 24.5 pixels. This average value was, however, within a wide confidence interval of errors between 3.6 and 201.9 pixels, where the median value was 16.7 pixels.

The average MARE recorded in this observation stage was equal to 0.14 (14%). Average MARE is a measurement to evaluate the performance of all participating volunteers on the single event.

The sample of volunteers active in the observation stage presented heterogeneous qualitative attributes in terms of education, university career background, and environmental expertise. Sample heterogeneity prompted to verify possible impacts of the qualitative attributes on the volunteers' performances. Figure 4.6 shows the distribution of the absolute mean error for each category within groups (1) educational level, (2) university career path, and (3) environmental expertise. Interestingly, there is counterintuitive evidence, indeed, that the lowest mean absolute error (16.2 pixels) was provided by undergraduate volunteers while the highest values are recorded among those who have a master's degree (MAE = 64.6 pixels). Similarly, it was not expected that, considering university career paths, that the lowest error (10.7 pixels) is provided by those who follow a career path in law disciplines. No considerable differences were reported related to environmental expertise. In fact, the difference in MAE between the environmental expertise group and the no-expertise group was 5.3 pixels. These results, however, do not reflect the specific trend of each individual group, but rather the distribution of outlier values among individual volunteers linked to personal biases and uncertainties.

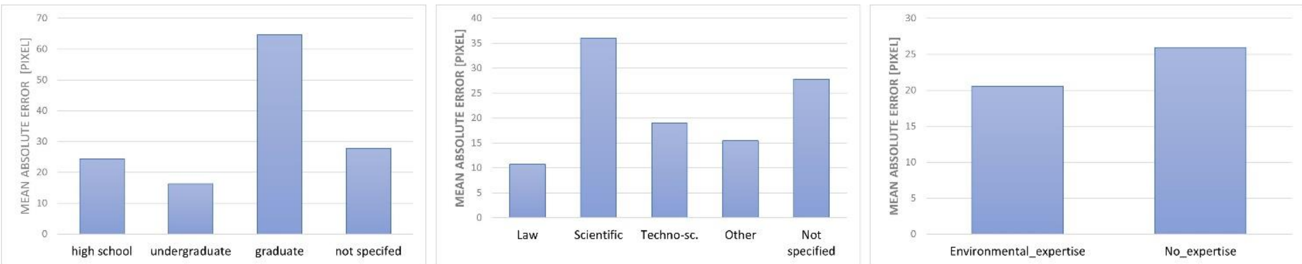


Figure 4.6. Mean absolute error (MAE) in initial observation stage sorted by qualitative attributes of volunteers: (left panel) educational level; (central panel) university career path: (right panel) environmental expertise.

Personal biases were also confirmed in Figure 4.7. The continuous distribution (Y-axis) of the stream-water level is uneven due to the uncertainties recorded for each image (X-axis) by each student volunteer (Z-axis) in the observation stage of the study.

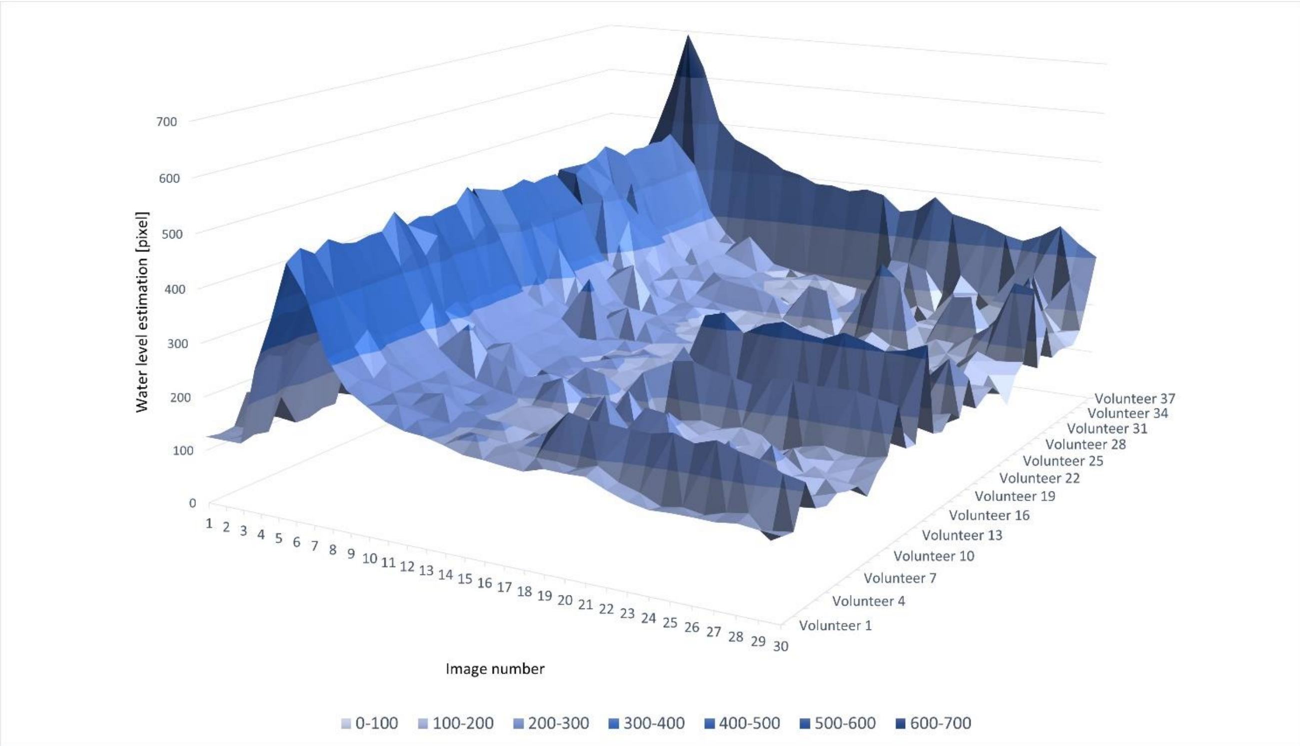


Figure 4.7. Flood wave reconstruction from collected student volunteer observations.

4.4.2 Preliminary insights from replication stages

We replicated the methodological procedure for estimating stream water levels and extended the observation activity of the student volunteers to two additional replication stages. The replication of observations had four main purposes: (1) increase the amount of data collected to obtain more significant estimates; (2) test the validity of the methodological procedure; (3) test the motivations of volunteers; and (4) evaluate any variation in volunteer performance over time. Furthermore, we asked the 37 participants to observe a second continuous series of 30 images of a downstream site during the same rainfall event. Finally, researchers asked student volunteers to examine a third continuous series of 30 images relative to the initial upstream site during a different rainfall event.

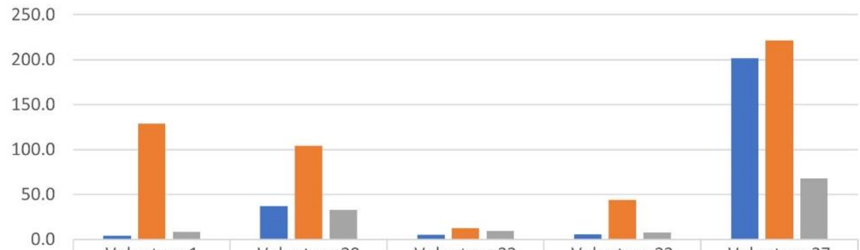
During the replication stages a drastic drop in participants was recorded, undermining the initial goals of this study. Only five volunteers replicated the observation activities of the water flow image series.

The secondary results provided an indicative insight into volunteers' performance and demonstrated the replicability of the methodological procedure designed for estimating stream water levels during a flood event. The limitation of the secondary sample size to only five observations did not permit analysis of these observations. Regardless, the results reported below showed the potential effectiveness of the proposed methodological procedure. The secondary results, which emerged from the small but motivated group of active student volunteers, showed promising variations - from the reduction of both the average MAE and the average MARE indices from the first stage of observations.

In the replication stage, the recorded average MAE among five volunteers also active in replication stages was equal to 120.2 pixels within a range between a minimum value of 12.4 pixels and maximum of 221.4 pixels. Compared to the observation stage, the average MARE increased to 25%. Regardless, focusing our attention on only the five consistently active volunteers, we noted a substantial improvement in performance across the first two phases of the study. Among the five consistently active volunteers, an average MARE equal to 28% at the first observation stage was recorded.

The same five volunteers completed the second replications stage and demonstrated strong interest in contributing to the citizen science experiment. In the final replication stage of the study, the average MAE was equal to 25.29 pixels, and the average MARE significantly decreased to 6%.

The MAE and MARE indices were useful in interpreting the performance of volunteers to better understand if during the different stages of the study, volunteers had acquired a greater ability to provide reliable observations. Outcomes from MAE and MARE pointed out a decreasing margin of error in the performances of five consistently volunteers across the three observation stages. The decreasing trend is also confirmed by the error distribution within volunteers (Fig. 4.8), where recorded error was attributable primarily to one participant.



	Volunteer 1	Volunteer 20	Volunteer 22	Volunteer 23	Volunteer 37
Series1	4.5	37	5	6.1	201.9
Series2	128.7	104.3	12.4	44.2	221.4
Series3	8.2	32.8	9.5	8	67.9

Figure 4.8. Mean absolute error (measured in pixels) of the five volunteers over the three stages.

The limited sample size does not permit generalization of the effective changes recorded in the observation skills of volunteers. Furthermore, the small number of volunteers does not allow us to fully understand the possible impacts of the training activities across the three different stages of the study. However, the convergence of observed values around the median values, especially in the final replication stage, suggests that the repetition of simple tasks, by small but motivated groups, can lead to an improvement in volunteer performance.

4.5 Insights from the first case study

In this case study, concepts and methods of citizen science were empirically tested to improve innovative procedures for hydrological monitoring. The active participation of 131 volunteers, among the large number of students who participated in the in-person initial workshop (around 400 people), addressed the researcher's decision to work remotely with the support of web-based cloud technologies to permit the collection of a large set of observations.

Student engagement in the role of observers was purely based on volunteer assistance. No incentives or remuneration was provided to support or motivate the participation of volunteers. They did, however, gain a sense of engagement and learned about selected study methods during the activity. Our aim was to analyze the student participation and to understand – also at an indicative level – the possible motivations that encouraged student volunteers to take an active part in a scientific research process.

The choice of voluntary participation obviously entailed risks that limited the dynamics of participation. Considering the initial group of 131 participants, in fact, only 37 volunteers contributed to the further development of the project by successfully performing the first observation stage test. In the replication stages, we found a drastic drop in participation, where only five volunteers contributed.

The difference between active and passive volunteers is a common issue within online communities. The active participation of 37 out of 131 volunteers can be considered a satisfactory result. On the other hand, the drastic drop in participation during the replication is an aspect that needs to be investigated. Authors hypothesize that this drop in participation is due to the following three factors: (1) repetitive tasks were requested; (2) there was a gap between communication and organizational phases of the project; and (3) the participants lacked substantial interest and motivation over time. At the present, these are only hypotheses and further investigations are required for future work on how to increase and maintain volunteers' engagement over time.

From available data indicative insights on the background of participating student volunteers can be derived. Among the 37 active participants, 25 volunteers declared to have a university degree (21 bachelor's degrees and 4 master's degrees). However, this is not particularly significant in a sample limited to university students. On the other hand, more relevant indications can be derived from the declared university career background. Most participants (41%) stated they were on a technical-scientific career path, and 32% were on a scientific pathway.

A higher educational level, combined with a disciplinary affinity with the hydrological monitoring study, seems to be a logical reason for active and lasting participation of a volunteer. This contrasts with other types of university careers that do not have an affinity with hydrological monitoring and could explain why only five students participated in the two replication stages of the research. One unexpected behavior has to do with volunteers with environmental expertise. The lack of environmental expertise does not seem to have a major impact on participation in the project. Of the 37 volunteers, a smaller percentage (38%) stated that their environmental experiences were obtained primarily from service in military corps activities related to environmental issues. Other students stated their environmental experiences were gained through job-related purposes. This is reasonable since students are still undergoing academic and professional training. In the light of the experiment carried out, there is, therefore, no common matrix that justifies long-term participation. However, there are indications that require further investigation. Further input derived from a follow-up questionnaire, which focuses on the analysis of motivations of student volunteers.

At the end of our experimental citizen science test, research team asked student participants which of the following motivations led them to participate in the project: (1) interest in environmental issues; (2) scientific curiosity; (3) personal satisfaction; (4) desire to be part of a scientific community; (4) sense of duty; (5) contributing to scientific research; (6) opportunity to improve knowledge and skills; or (7) environmental sensitivity. The replies received focused on three primary aspects: (a) interest in environmental issues; (b) contributing to scientific research; and (c) opportunity to improve knowledge and skills. The volunteers unanimously stated that they were very satisfied with the experience gained and moderately satisfied of their improved knowledge and skills. They also agreed that their contribution has been useful for scientific research. However, student volunteers stated that their level of awareness regarding environmental issues remained unchanged.

What is evident from the initial observations is the constant participation of a small but motivated group of volunteers (total = 5) in all stages of the project. Another aspect is the reliability of the observations and the trends in performance, as attested by the average MARE index equal to 0.14 in the peak of total participants (37 volunteers). The general convergence of water level estimations from volunteer observations, and the relative low average MARE index (0.14), are probably affected by training. This allowed each volunteer to replicate autonomously and remotely the methodological designed for data acquisition through direct observations. Therefore, it appears that the training allowed, albeit in a limited and restricted sample, the replicability of the methodological procedure of data acquisition. This was achieved through direct observation of a continuous series of images, relative to different sites and rainfall events, during the replication stages. The average MARE index, equal to 0.06 obtained in the last replication stage, is an encouraging sign – albeit it was obtained from a very small sample.

In general, we have not found incidences of qualitative variables related to the backgrounds of student volunteers, but rather the results are conditioned by outlier values resulting from the subjectivity of the single observer. However, we do not have a significant sample size to provide more detailed assessments of the incidence of qualitative variables. This aspect of the research identified a general improvement in volunteer performance due to the use of simple, repetitive tasks.

The data used in this study are not included into the category of User-Generated Contents (UGC), as they were not released through social media or digital platforms (Zheng et al., 2018; Sy et al., 2019; See et al., 2019; Modaresnezhad et al., 2020). Rather, data was acquired using crowdsourcing methods according to precise protocols set in the research design phase of the study (Brabham, 2008; Estellés-Arolas et al., 2012; Palacios et al., 2016; Martinez-Corral et al., 2019; Lowry et al., 2019).

Our data collection activity conforms to the contributory typology of citizen science (Gray et al., 2017; Bonney et al., 2016; Aristeidou et al., 2017). The contributory approach indicates that research questions and research design adapt to a top-down research process coordinated by expert scientists. The role of the volunteer is limited to interpretation of guided data collection. Subsequently, data processing and analysis therefore remain with the competence of the experts.

Volunteers' engagement, however, is applied to the dissemination of results, with the support of digital dashboards, to increase knowledge and awareness on issues related to environmental management and monitoring, and awareness of sustainability and conflict reduction related to the improved use of water resources. Public engagement during information dissemination is also important because it will highlight the role of the volunteers in the formulation of scientific knowledge. This is useful not only for research but also for setting decision-making scenarios for the public to be included, informed, and active participants in the process.

Our first case study evaluated some principles of citizen science, to obtain estimates of water levels in an ephemeral stream, through visual image analysis. In this regard, we designed a procedural protocol for the validation of volunteer observations. The procedure was assessed on the Montecalvello river basin, but it is replicable in other geographic settings. To evaluate the validity of the research methodology, we relied on a sample of university students from the Tuscia University community to establish a controlled group of volunteers.

The MAE and MARE of volunteer observations yields satisfactory and promising results in terms of the reliability of data from volunteered observations. The average MAE of 24.5 pixels implies that the overall error margin recorded by the volunteers is 70 mm (1 mm = 0.35 pixel). The smallest recorded MAE of 3.57 pixels implies that the margin of error obtained is 10.2 mm. Furthermore, the data shows a decrease in the margin of error from the first to the last phase, indicating how training and replicability can affect the improved validity of the data obtained.

The application of the pilot case has been useful to highlight issues and limits related to the effective participation of volunteers and the reliability of their observations. The adoption of communication techniques, aimed at encouraging participation and the application of the test on a controlled sample, however, affected the activity of the volunteers. The main issue encountered during this work was the recruitment and engagement of student volunteers. We found that it was difficult to maintain high and constant motivation of volunteers since they did not appear to be motivated - in terms of material gain - in the scientific research activity. Continuous communication campaigns to update and encourage participation in the various phases also had very limited effects.

As a result, this research assesses the difficulty of establishing stable and lasting volunteer communities for citizen science projects, regardless of whether they are in-person or virtual online communities. In our study, we experimented with a mixed mode of approaches in which, at the initial phases of in-person recruitment through classroom workshops, we followed up with activities through online methods. This leads us to conclude that a greater effectiveness of citizen science projects can be ensured by temporally limited activities which are addressed to limited groups of participants who are strongly motivated by common interests, and personal or collective appreciation for the proposed research topics. In our study we adopted a contributory approach, where research questions and methodologies followed a top-down model. Approaches related to other types of citizen science – such as collaborated or co-created – could provide different indications of the motivations that support volunteer participation. Regardless, a scientific research activity established on a bottom-up approach would imply a greater level of participation and involvement but could not be established in our specific study.

5. POP-Rain: citizen observations of spatial rainfall intensity

5.1 Foreword

The second case study was focused on testing the capabilities of citizens to act as sensors to collect rain data. As seen in previous sections of this thesis, citizen science is widely tested for the study and understanding of hydrological processes and water resource management. Citizen input is essential to increase the quantity and distribution of observations by offering low-cost and easily applicable alternatives in contexts exposed to morphological and environmental risk. Advances in citizen science allow experimentation with volunteer engagement procedures and data collection through the support of web-based technologies. Indeed, in the context of digital transformation, modes of participation in scientific research processes include the inclusion of interacting virtual communities within thematic platforms, such as meteorology. The application of online citizen science brings benefits both in terms of data acquisition and availability; and the speed of communications underlying the organization of activities especially from remote locations.

The POP-RAIN project was designed by researchers at the University of Tuscia to test the ability of citizens to provide qualitative rainfall information through simple and straightforward data acquisition procedures supported by digital technology solutions. POP-RAIN is a polyhedric and multidisciplinary project that includes aspects related to hydrology to define research problems and data validation methodologies; aspects related to social and organizational sciences to design and operationalize long-term engagement procedures; and aspects related to computer science to design and implement tools suitable for engagement and performance of volunteer activities. At present, the project is still in an embryonic stage, in which the research work is geared toward analyzing the actual abilities of citizens to provide valid observations of rainfall. This step is preparatory to the implementation of future engagement activities on specific volunteer targets. In this regard, the development of a smartphone app is presented here as an output of the research activities conducted. In this section, the POP RAIN case study is presented in the form of a draft paper next to the submission summarizing the objectives and ongoing design and development phases of the POP RAIN project.

The development of an application is functional in solving two of the main problems in the field of citizen science:

- At the technological level, providing tools that facilitate data collection by reducing the margin of error in observation through geolocation and automatic synchronization features.
- At the organizational level, facilitating the establishment of an active community through messaging extensions, alerts, and interactive dashboards for sharing results.

The core of the PhD research activity is the development of an application to support data collection activities for hydrogeological monitoring through the development of an active volunteer community. The development of digital technology solutions is one of the initial goals of framing activities and participatory modes in the context of digital transformation interactions. Online communities become new players whose potential is yet to be explored.

5.2 Introduction

Citizen science is a fascinating emerging discipline whose aim is to involve citizens in the advancement of knowledge. In hydrology, the contribution of citizens can be pivotal to increase the space and time distribution of observations, which is challenging due to the heterogeneity of hydrological processes (Breuer et al., 2015; Koch & Stisen, 2017; Mazzoleni et al., 2017; McCabe et al., 2017; Walker et al., 2021).

The use of citizen science methods has experienced a significant increase in rainfall monitoring (Starkey et al., 2017; Tipaldo & Allamano, 2017; Paul et al., 2020; Alfonso et al., 2022). Case studies are being conducted in various regions of the world, pursuing the common goal of filling data gaps, related to an uneven distribution of official rain gauges or the high cost of technologically advanced remote sensors (Buytaert et al., 2014; Walker et al., 2021; Weeser et al., 2018; See, 2019; Alfonso et al., 2022; Tedla et al., 2022b). Wherever it is applied, citizen science is a solution that researchers in the field of hydrology rely on. However, common problems relate to (1) social and cultural barriers that often limit participation; (2) outreach for volunteers to be involved in data collection and scientific research activities that require sustained and ongoing commitment. An additional issue then concerns the reliability and validity of data provided by non-expert citizens (Fehri et al., 2020; Shinbrot et al., 2020; Tedla et al., 2022). This issue depends on numerous tools (e.g., technologies used) and socio-cultural (educational and cultural background, expertise) factors (Shinbrot et al., 2020; Tedla et al., 2022). Cognitive and behavioral biases can affect the quality of the data on which studies set on citizen science are then based. A univocal answer to each of the issues outlined does not exist. This is highly dependent on the exploratory and experimental nature of citizen science projects, whose procedures are adapted to the actual context of application.

The role those new digital technologies (i.e., smartphone app, digital platforms, social media) play in supporting Earth Observation and in monitoring hydrological processes with crowdsourcing techniques is widely recognized (Breuer et al., 2015; McCabe et al., 2017; Tipaldo & Allamano, 2017; Paul et al., 2018). The use of new digital technologies in citizen science brings benefits in terms of: (1) semi-automated extended data acquisition; reaching a larger number of volunteers, crossing social and cultural barriers; (3) immediacy of processes and activities carried out by volunteers; and (4) faster and more efficient communications within organized communities of volunteers through the exchange of data, information and feedbacks. Starting from these theoretical premises, a group of researchers from the University of Tuscia launched the POP-RAIN project in 2017.

POP-Rain (i.e., POPular Rain) is a citizen science project that aims to verify if citizens can provide qualitative information on rainfall. The citizen-based observations work as follows. First, during a rainfall event, citizens are invited to quantify rainfall intensity just by looking at the natural phenomenon. Then, POP-Rain volunteers indicate their perception of rainfall intensity through a survey form, whereby rainfall intensity classes are reported. By collecting citizens' feedback, the POP-Rain survey provides the citizens' geographical position and observations in real time.

From its beginning, POP-RAIN is being coordinated by faculties from different departments, highlighting the transdisciplinary nature of the project by integrating epistemological aspects and research problems related to hydrology and Earth Observation with research methods from the social sciences (volunteer engagement, motivational and behavioral aspects) and computer sciences for the design and development of appropriate technological solutions. The project, still in progress, is in an implementation phase towards a virtual context.

A pilot test was conducted among the students' community of Tuscia University in order to test the methodological procedures of data acquisition and validation from volunteers. 150 volunteers have been operating since 2017, thus providing more than 300 observations.

An exploratory case study was recently conducted to test virtual engagement strategies toward establishing an online community active in rainfall monitoring. The purpose of the online engagement activity is to extend and diversify the users based on qualitative factors such as age and educational and socio-cultural background. Such differentiation will be used, at a late stage of the project, to identify specific user targets based on shared interests and motivations to support participation. At this stage, about 80 observations were collected and analyzed, replicating in a virtual setting, the procedures through which volunteers were asked to indicate their direct observations within qualitative classes on rainfall intensity. Future implementations of the project include the use of a smartphone app aimed at refining techniques for capturing observations and engaging groups of volunteers.

In this contribution, we review the design and implementation phases of the POP-RAIN project. Starting from the preliminary observations of the pilot test, the replication phases are described and then dwell in the design of the app. In Section 5.3, the contribution describes the methodology for capturing observations by defining qualitative classes. Section 5.4 focuses on the results acquired in the replication phase from the preliminary studies. Sections 5.5 and 5.6 provide discussions and conclusions by plotting the way forward through the design of the smartphone app to support future development and engagement campaigns of POP RAIN.

5.3 Materials and methods

The development of the POP-RAIN project is divided into two phases of implementation of the methodological procedures for the acquisition of data by direct observation on precipitation: pilot case and replication phase. A third parallel phase focuses on the development of a smartphone application to support future project activities according to citizen science approaches.

The pilot case is a preliminary study of the project, aimed at developing the methodological procedure of data acquisition by a sample of volunteers recruited at Tuscia University. Students were invited to be part of the project and they were selected from all the University courses in order to have a heterogeneous cultural background population (i.e., humanistic and scientific) within a controlled group. Once enrolled, volunteers were instructed on the rainfall observation procedure through a Google Form. The form allowed volunteers to interact with POP-Rain staff and to submit their feedback on precipitation.

The proposed citizen-based monitoring procedure is quite simple. Volunteers should take note of the day-time and their position, the duration of the observation, and pre-existing weather conditions. Further, the form includes a rainfall intensity classification that consists of seven qualitative classes of rain intensities [mm/h] from < 1mm/h to >30mm/h, as standard unit of measurement for precipitation (table 5.1). For example, if a volunteer observes a rainfall for the duration of 10 minutes, assuming that a water level of 10 mm has accumulated in a raingauge, this means that the intensity is equal to 60 mm/h. Volunteers are asked to observe precipitation at least for five minutes and then select a rainfall intensity class based on their own perception of the observed rainfall event.

Qualitative observation scale	**Quantitative reference**
Drizzling	<1 mm/h
Very light rain	1-2 mm/h
Light rain	2-4 mm/h
Moderate rain	4-6 mm/h
Heavy rain	>6 mm/h
Downpour	>10 mm/h
Cloudbursts	>30 mm/h

Table 5.1. Qualitative classes of rainfall intensity.

Since the beginning of the project, the POP-Rain staff has contacted volunteers only twice, at the beginning of rainfall events following long dry periods. The first step of the project was the evaluation of the volunteers' performance. This was assessed by comparing citizen-based data to precipitation intensities measured at the rain gauge closest to the volunteer. In this first preliminary presentation, researchers analyzed 107 observations collected within 2.5 km from a rain gauge.

In the second phase, the data acquisition methodology was replicated by experimenting with online recruitment approaches. Groups of citizens were invited to take part in the project by disseminating the survey through social media platforms to make the sample of volunteers wider and more heterogeneous in educational and cultural terms.

Through the survey, participants were invited to provide first contact information for the unique identification and coordination of communication campaigns to support the project. Qualitative information on age, educational and cultural background have been used for the profiling of the volunteer and for identifying possible effects in the ability to provide reliable observations. Finally, the volunteer was invited to indicate the intensity of rainfall observed within the same seven classes of values illustrated in table 5.1, the location and the time of observation to allow comparison with official rain gauge.

To establish the comparative official rain gauge, an algorithm in GIS environment to measure distance was performed. Given an origin and a destination layers, algorithm computes the distance between origin features (volunteered observation) and their closest destination one (nearest official rain gauge) by the linear kilometer distance. Then, we considered the date, time and duration of the observation to determine the time frame within which to make the comparison.

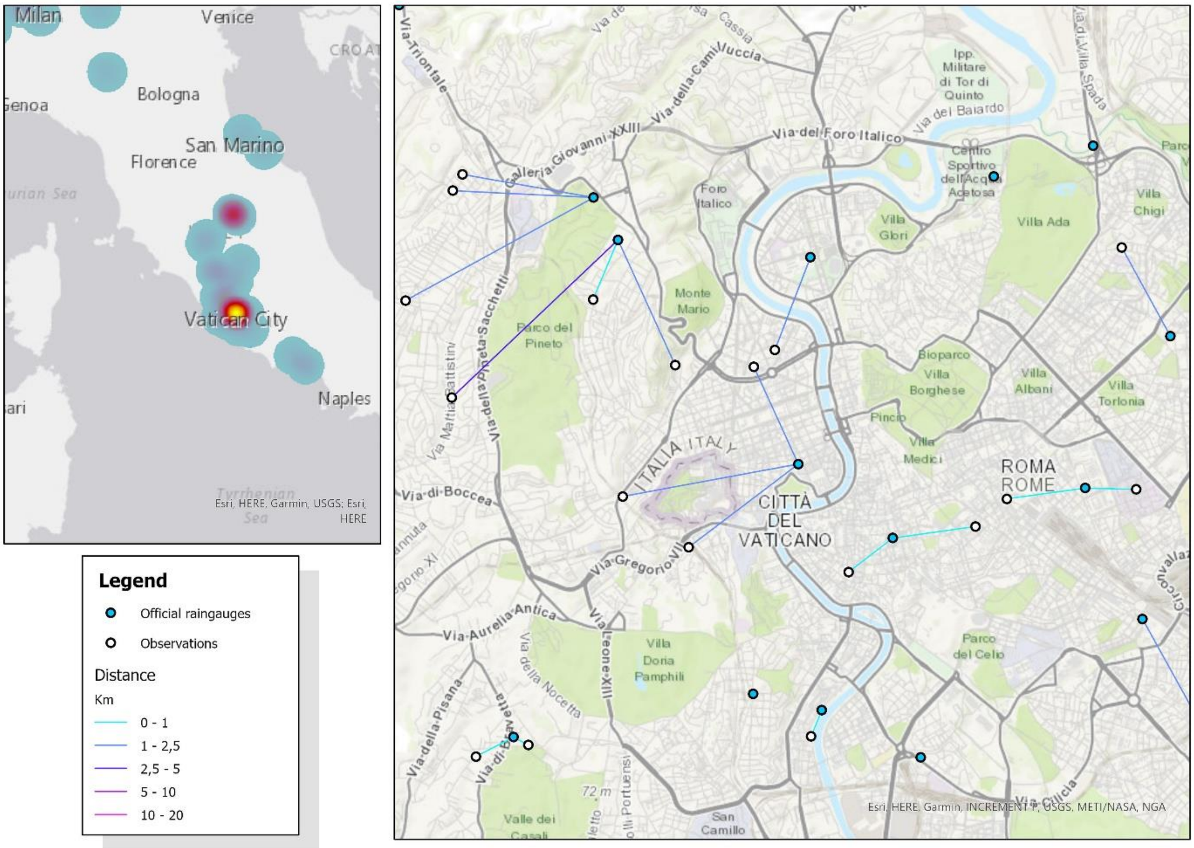


Figure 5.1. Concentration of total citizen observation (left side). A frame from distance analysis to find nearest raingauges from volunteers in the city or Rome (right side).

The rainfall observations were carried out in 5 Italian regions: Lazio, Umbria, Lombardy, Emilia Romagna, Marche and Piemonte (Figure 5.1). Official rainfall data were provided by the civil protection departments and regional environmental protection agencies by direct request. The comparison between the observed value and the measured value allowed to determine the discrepancies of the voluntary observations within the qualitative classes on the intensity of rain, shown in Table 5.1.

5.4 Results

Figure 5.2 shows the comparison between citizen observations and rainfall measurements obtained in the pilot case of POP-RAIN project.

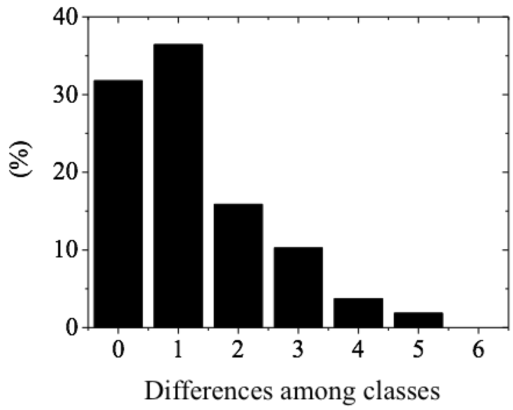


Figure 5.2. Differences between the citizen rainfall intensity during the pilot case. In x-axis the differences between the citizen rainfall intensity class observation and actual raingauge intensity class. In the y-axis the percentage of observations.

Notably, more than 30% of the observations agreed with the raingauge (bar 0 in Figure 1), and more than 35% of the observations showed an error of only one class (bar 1 in Figure 1). Therefore, almost 70% of the observations were correct or reasonable. Vice versa, only 10% of the observations were totally misinterpreted.

The reason for such discrepancy was due to a multitude of factors. In addition to the obvious inaccuracy of the visual estimation, performance can be affected by the spatial heterogeneity of rainfall that within 2.5km could still impact the validation.

These results were consistently reflected in the analyses carried out in the replication phase. To reduce discrepancies arising from distance and possible inaccuracies, we adopted two analysis strategies: (1) automatic approach; (2) manual supervision. In the first case, we analyzed observations on fixed time intervals, that is, in the 30 minutes before and after the time indicated by the volunteer. In the second case, analyses were carried out on variable time intervals, defined by the duration of observations stated by the volunteer. The second approach was implemented to check the effectiveness of automatic control. The two approaches did not result in significant variation. The results obtained with the first approach are shown.

In the replication phase, almost 40% of observation agreed with the official rain gauges (as illustrated in bar 0 in figure 5.3) and more of 25% of observation showed an error of only one class (bar 1 in figure 5.3). Almost 65% of the observations were correct or reasonable, in coherence with results from pilot case. Also in this case, the discrepancy was due to the same factors related to visual estimation and distance from official rain gauges.

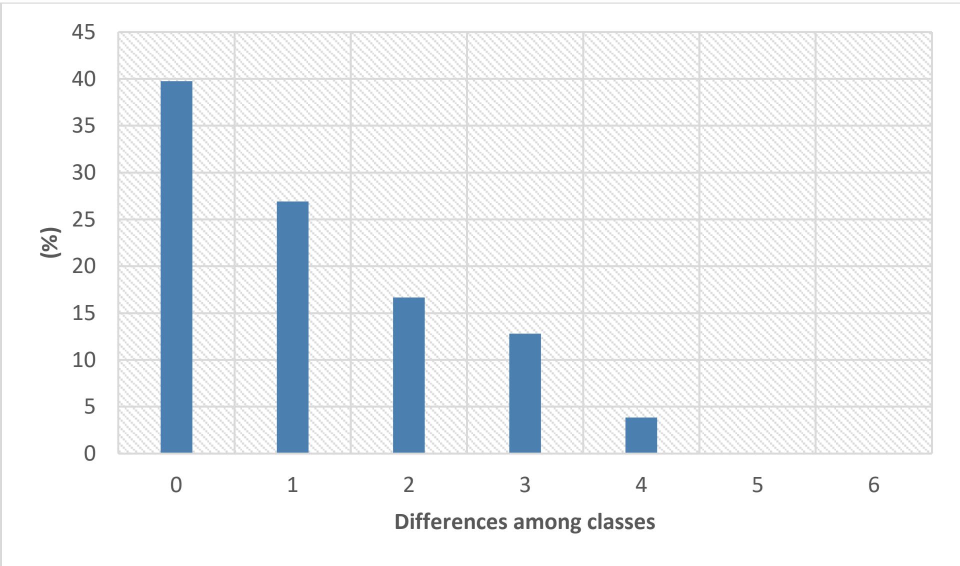


Figure 5.3. Differences between citizen rainfall intensity class observation and actual raingauge intensity class. In x-axis the differences between the citizen rainfall intensity class observation and actual raingauge intensity class. In the y-axis the percentage of observation. Graphic depicts generalized analysis to all events (n = 78).

The latter aspect was particularly pronounced in the replication phase. A significant number of observations (n = 53) were made at more than one kilometer between observation point and rain gauge. Of these, about half were over 2.5 km. Figure 5.4 shows how the rate of correct or reasonable observations within 1 km increases significantly, with a value of 72% (total aggregate percentages classes 0-1). However, at a distance beyond 1 km, the percentage of correct or reasonable observations is 64.2 percent (Figure 5.4). These results support the hypothesis that the discrepancy problem is not only related to the observer but also to the heterogeneity of precipitation.

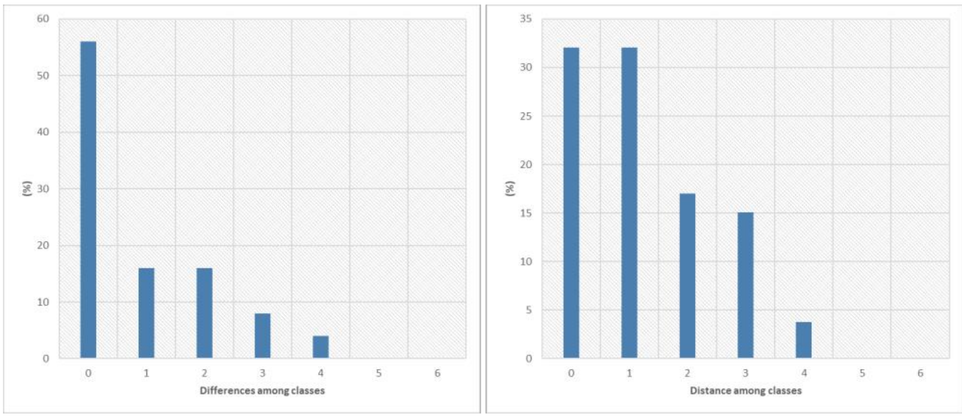


Figure 5.4. Detail of the generalized analysis of the distance from the rainfall meter. In the left pane, analysis of observation <1km. In the right panel, analysis of observations from a distance of more than 1 km.

Another emerging hypothesis is the general ability of volunteers to provide correct or reasonable observations on high intensity (>6mm) precipitation. Figures 5.5 and 5.6 show that the rate in classes 0 and 1 is about 85 percent, compared with low-intensity precipitation (<6mm), where the rate drops to 60.4 percent. These results may be intuitive because intense events are generally more identifiable.

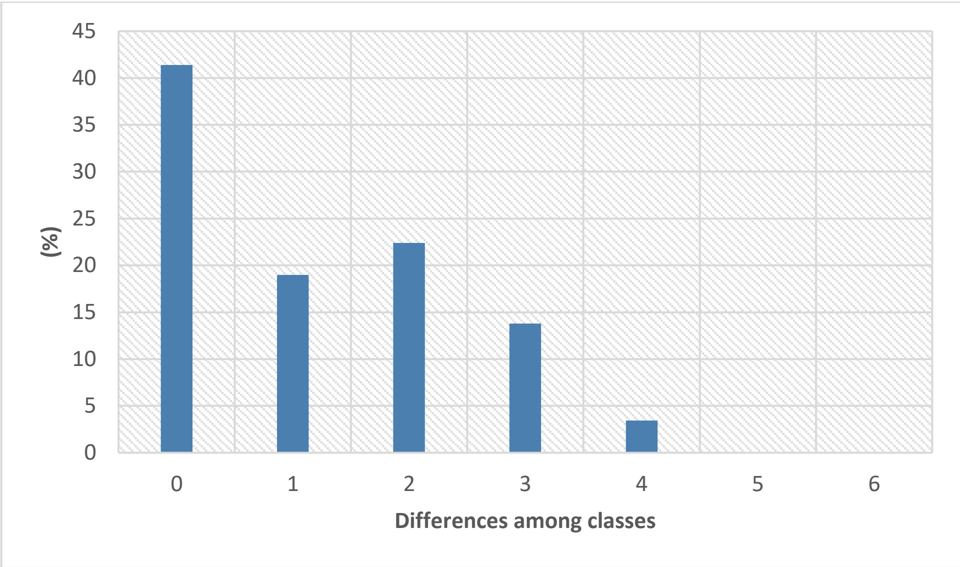


Figure 5.5. Graphic focused on the analysis of all rainfall events <6mm (n=58).

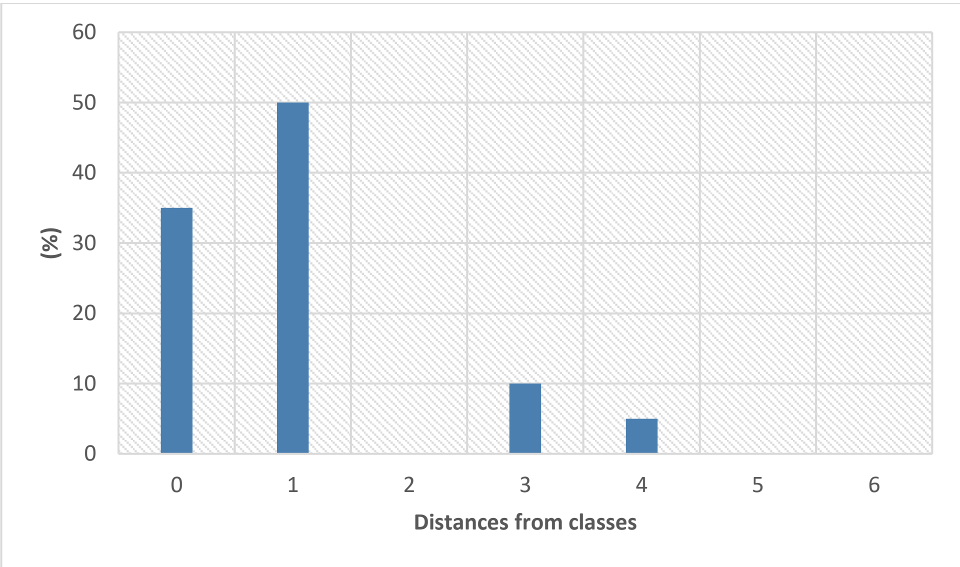


Figure 5.6. Graphic focused on analysis of all events >6mm (n=20).

However, distance remains a factor influencing volunteers' observations even in the case of heavy rainfall. Figure 5.7 shows that within 1km the correct or reasonable observations are about 87% versus about 58% beyond 1km distance.

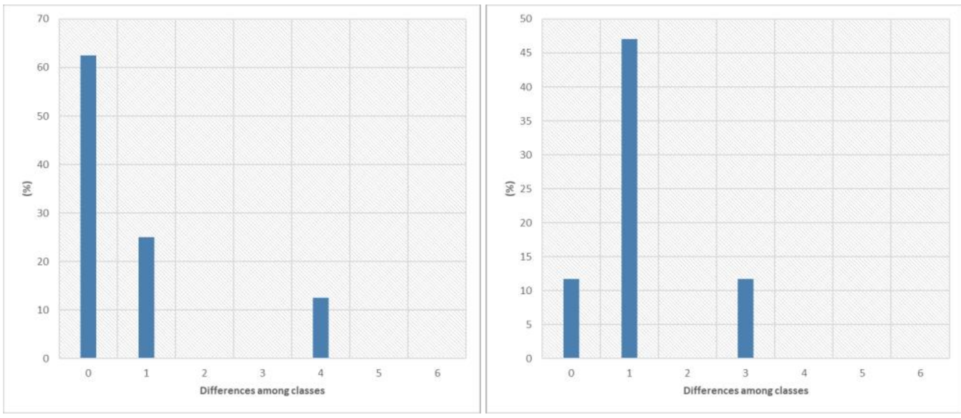


Figure 5.7. Comparison between all heavy rainfall events (>6 mm). Observation within 1 km (left side) and observation over 1 km (right side).

5.5 Findings and future development of POP-RAIN project

5.5.1 Findings from results

Considering that observations provided by citizens are performed just visually, without any scientific background, specific training, nor mobile instrumentation, we consider these preliminary results unexpected and particularly promising. Surely, the performance can increase improving the methodological approach, and future work will aim to identify the optimal conditions for volunteers to provide accurate observations.

The results obtained must also be interpreted considering the small number of observations collected at this exploratory stage of the work. A larger number of observations would provide a closer assessment sample to the values measured by the rain gauges and thus the possibility to better assess the reliability of the observer. To make the comparison between the observed value and the value measured by the rain gauge, the variables considered were date, time and location stated by the volunteer. The rain gauge data were then aggregated over a time interval of 30 minutes before and after the time stated by the volunteer. In this way, the observation was compared with the hourly precipitation trend. The findings bring out a difference in performance related to the distance between rain gauge and observation location. The highest performance was recorded within 1 km (n = 25). This finding is probably due to less heterogeneity of the rain event at a small distance.

Higher error margins were found at a distance greater than 1 km, as attested in Figure 5 where the incidence of classes 2 and 3 is higher. In some of the cases, however, it was difficult to establish the reference rain gauge due to the inaccurate location provided by the user. In general, the high percentage of correct or reasonable observations (especially in cases of heavy rainfall above 6 mm/h) highlights the potential of citizen as sensor in rainfall monitoring and pushes toward the implementation of new solutions for more accurate observations and better performing engagement strategies supported by the adoption of digital tools. A topic to be explored further in future phases of the POP RAIN project relates to ways of long-term engagement and supporting volunteers' motivation to participate. This issue is very common in the continuation of citizen science initiatives. A particularly critical issue in the POP RAIN project also concerns the frequency of rain events. Planned activities were slowed down and scaled back due to low rainfall, which affected volunteer engagement and activity. As such, future implementations of the project should take into consideration continuous and direct alert systems and messages to stimulate volunteer participation.

In the second replication phase, the team of researchers disseminated POP RAIN project membership messages on social media channels, selecting online community targets interested in environmental and weather issues, during heavy rain events. Volunteer response was immediate upon receipt of the invitation but did not result in continuous actions during subsequent events. This attitude supports the hypothesis that constant motivation must be sustained by continuous interactions with volunteers to keep the threshold of attention and interest high. Future implementations of the POP RAIN project should therefore consider the development of engagement tools to support information exchange and feedback to increase interactions and the level of engagement in the project.

5.5.2 The way forward: POP-RAIN app

To address the critical issues that emerged, both at the technical and engagement levels, the research team designed a smartphone application. The application is the technological solution to support the implementation of POP-RAIN-related activities. At present, the application has been tested in beta version for Android® devices. A version for iOS® devices is under development. The development of the app is also preparatory to initiating and establishing a community of citizen scientists to be involved in rainfall monitoring activities. In this regard, alert systems and operational dashboards are extensions that researchers are considering supporting engagement activities. The logical structure of the app is designed to collect data on the time, duration, and location of the observation. In this way, the information is refined through synchronization with GPS technologies and the calendar functions of the host device. In addition to exact location, the advantage of GPS technology is to provide indications of the elevation of the observation. This makes it possible to monitor the precipitation event upstream and make timely forecasts downstream.

The app's features are designed to make the collection of rain observations intuitive and automatic. The flow chart in figure 5.8 summarizes the architecture of the app. The app architecture will be described in the appendix of this chapter.

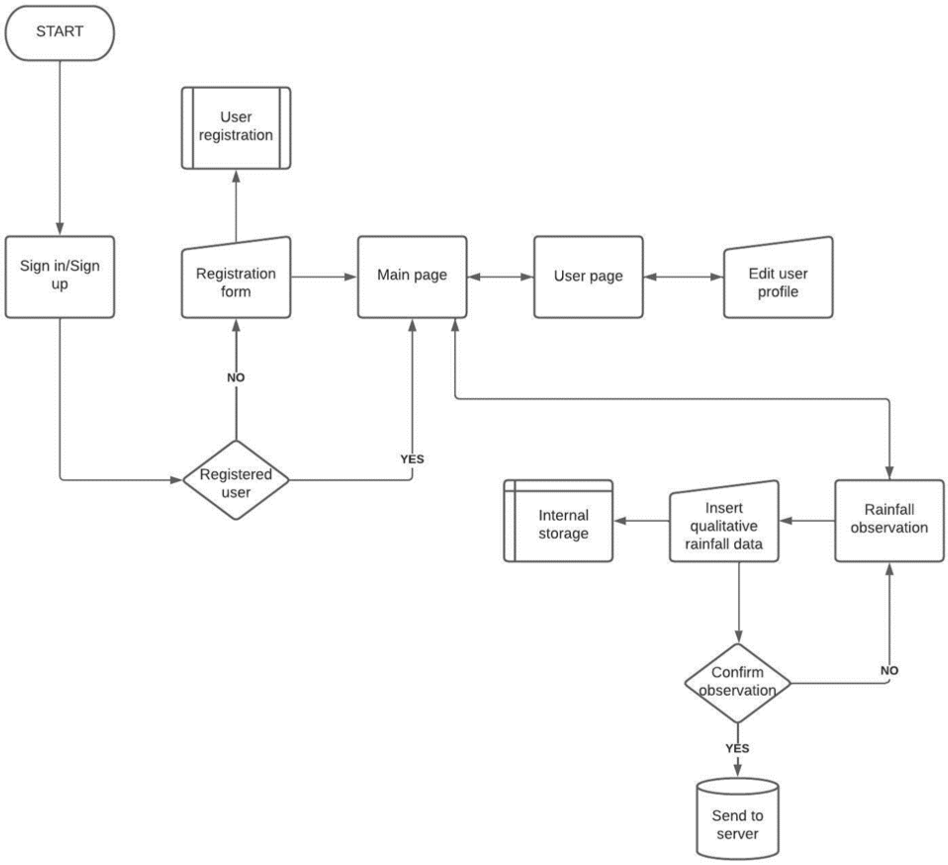


Figure 5.8. Flow chart of the POP-RAIN smartphone app architecture.

5.6 Insights from the second case study

The second case study presented the design and development stages of the POP-RAIN citizen science project. The project, launched in 2017, is in a testing and integration phase with online citizen science modes. The work done so far, however, has enabled useful findings for the implementation of the project, highlighting the potential of involving citizens as sensors in monitoring rainfall and hydrological processes. The limitations of this study are mainly instrumental. The instruments used so far leave room for approximation and inaccuracy in the direct observation activity by the volunteer. Reducing these approximations and inaccuracies allows for more accurate evaluation of volunteers' performance. In this regard, the application of citizen science principles in an exploratory case study enabled the research team to understand the critical issues related to citizen involvement in research and monitoring activities and design suitable solutions to reduce inaccuracies and uncertainties. The results obtained and presented here show the potential of citizens to provide reliable rainfall information and of citizen science methods as an integration to traditional but economically expensive monitoring techniques. At the same time, the findings allow the foundation to be laid for future implementations of the project, in which the level of transdisciplinary integration will serve to identify suitable strategies and tools for volunteer engagement.

Part III: Discussion and conclusions

6. Discussion

6.1 The issue of creating a community of citizen scientists

This thesis work traces a research path aimed at investigating citizen science as an innovative research approach for the study and awareness of hydrological and environmental change. After defining the theoretical framework, the research followed an empirical approach based on designing and conducting exploratory case studies to understand the potential and limitations of citizen science. The efforts of this research are part of the scientific debate promoted by Citizen AND HYdrology (CANDHY) working group within the International Association of Hydrological Sciences (IAHS) to define conceptual and organizational models to promote participatory science initiatives on the topic of water governance.

The case study as a research method is therefore the appropriate option to derive lessons and useful feedback to define common procedures that can be replicated in different contexts. The case studies related to Montecalvello basin monitoring (chapter 4) and rainfall observation in the POP-RAIN experimental project (chapter 5) address precisely needs to test principles of citizen science as an iterative process based on trial and error to conduct first-hand experiences.

According to Yin (2017), the case study represents a precise methodological choice when three conditions arise: (1) when the research question investigates the "what" and the "how"; (2) when there is no control over behavioral events; and (3) when studying a contemporary phenomenon (Yin, 2017).

The primary reason for designing case studies was to understand how citizen science can contribute to advances in hydrological research and what lessons can be learned from its application. In particular, what real contribution non-expert citizens can make in the processes of scientific knowledge production and environmental awareness.

The second reason to adopt case-study as a research method was the lack of control over behavioral events. The case studies presented here are both in their early stages. Therefore, for the purposes of this research, it was important to investigate the involvement and interest of volunteers in the research stages through ad hoc methodological procedures without influencing their behavior to understand the participants' actual abilities to provide reliable and valid data without any conditioning. The only limits imposed were of a technical nature to do the required tasks.

The definition of methodological procedures followed in part the guidelines provided by Jennett and Cox (2014) regarding the development of virtual citizen science projects: (1) task simplification based on volunteer expertise; (2) task support for volunteers through tutorials and training activities; and (3) incentive for participation through feedback on the progress of the work done. The decision to conduct multiple case studies was motivated by the need to get more feedback on the application of theoretical citizen science principles in a real-world context and to understand in detail the value of soft data and volunteer observations in hydrological monitoring (Blöschl et al., 2019). The two case studies were conducted separately, although they adopted similar protocols for data collection and procedures for validating observations based on comparison between volunteered observation and official or expert data as benchmark value.

The definition of methodological procedures of case studies has been a rather critical task considering the exploratory condition of the activities and the need to initiate a community of volunteers to be involved in first-hand experiences of citizen science. In this context, many questions have arisen about the motivations behind the participation of volunteers and about the recruitment methods to be adopted. In particular, the initial questions concerned the target to be involved in embryonic research activities. Indicative responses are derived from aspects related to recruitment and the motivations framed in the theoretical framework. A further investigation of case studies and best practices on citizen science allowed to understand in detail the main motivations and recruitment strategies adopted in other empirical contexts.

Barriers in the construction of a community of citizen scientists leads to the third condition posed by Yin (2017), i.e., the choice of case study research to investigate a contemporary phenomenon. Research approaches and strategies are therefore developed based on specific objectives and conditions peculiar to the study context. The overview of the motivations and strategies for engagement must be considered in general and orientation terms.

The literature review analysis revealed a fundamental concept: recruitment is intended as an act of identification and retaining of volunteers to build an active community of citizen scientists (Spasiano et al., 2021). To identify volunteers, the study of personal or collective motivations is essential to understand the behaviors and values that drive participation (Palacin et al 2020). The success of citizen science projects is linked to the ability to attract participants (Franzoni & Sauermann, 2014; Aristeidou et al., 2017; Lee et al., 2018; Cappa et al., 2018). Sustained participation represents one of the main challenges in conducting digital citizen science project (Foody et al. 2017; Jennett & Cox 2018; Orchard, 2018). Therefore, recognizing motivations, experience and personal or socio-cultural perspectives can assist the design and the implementation of citizen science projects (Palacin et al., 2020; West et al., 2021; Land-Zandstra et al., 2021). Matching motivations and perspectives could help in recruiting and retaining volunteers (Phillips et al., 2019; Land-Zandstra et al., 2021). Understanding the motivations is also useful to implement communication strategies targeted to the interests of volunteers. Studies about motivation in citizen science often use methods and tools from social sciences research, in which volunteers indicate the most important reasons that drove them to participation (Land-Zandstra et al., 2021). Among social sciences theories that explain the motivations behind participation, Self Determination Theory (Ryan & Deci, 2000) and the Schwartz Human Value Theory (Schwartz et al., 2012) are two important references to investigate on feedback relationship between actions, motivations and values (Palacin et al., 2020). According to Self Determination Theory, the motivations are based on the underlying needs that push people to undertake collective activities: autonomy (control over objectives and actions), competence (learning and skills), sense of belonging (Ryan & Deci, 2000). Schwartz Human Value Theory, however, identifies in universal values the motivations that guide individual actions: self-transcendence, conservationism, self-enhancement, openness to change (Schwartz et al., 2012). There is no common view on the motivations for volunteers to take part in citizen science projects. In general terms, people can be driven by personal interests or altruism (Rotman et al., 2014). In this sense, it is possible to identify intrinsic or extrinsic motivations (West & Pateman, 2016). The first group includes motivation to personal interests or values (West & Pateman, 2016), pressing needs or issues within a community (Frensley et al., 2017). The second group includes motivations derived from external inputs such as career advancements or rewards (West & Pateman, 2016; Cappa et al., 2018; Larson et al., 2020; Palacin et al., 2020).

However, it is quite common in the field of citizen science, the time-limited effect of motivation (Sauermann & Franzoni, 2015; Land-Zandstra et al., 2021). Volunteers tend to be driven to initial participation by curiosity, interest in science, and a desire to contribute to scientific research (Jennett et al., 2016). Long-term participation requires social obligation and continuous stimulation that requires time and ability (Jennett et al., 2016). Some studies have found that only small groups of volunteers actively contribute to the work (Sauermann & Franzoni, 2015; Land-Zandstra et al., 2021). Their contribution is often limited to once and then they abandon the project. This may be due to: (1) gap between motivation and expectations; (2) lack of coordination at the communication and organizational levels (Sauermann & Franzoni, 2015; Land-Zandstra et al., 2021; Agnello et al., 2022). Communication strategies set on continuous interaction and sharing of results and feedback are aspects to consider for long-term volunteer retention (Agnello et al., 2022).

Understanding motivation can help project leaders to set recruitment methods to engage targeted groups of volunteers according to their level of expertise and interest on the covered topics.

Even from the recruitment aspect, the experimental and empirical nature of citizen science influences the strategies and decisions of coordinators and project leaders. Defining recruitment strategies and tools for long-term volunteer involvement remains one of the biggest challenges in citizen science. On the one hand, reaching a large number of participants remains a key factor in the success of participatory approaches to scientific research (Cappa et al., 2016; Cappa et al., 2018; Lee et al., 2018). On the other hand, however, broad recruitment and retention may expose it to risks related to the reliability of the data collected (Arienzo et al., 2021). Large participation ensures the sustainability and temporal continuity of citizen science projects (De Moor et al., 2019; Arienzo et al., 2021).

Online tools and resources nowadays provide affordable, bridge-to-use options for engaging and training a wide range of volunteers (Frensley et al., 2017; Cappa et al., 2018). Digital tools also make it possible to make the procedures of research activities faster and more efficient (Cappa et al., 2018). An additional advantage of digital technologies and platforms is to facilitate interactions between volunteers and project leaders, the exchange of data, information and feedback (Cappa et al., 2016; Capdevila et al., 2020; Davis et al., 2020). Finally, online platforms foster self-learning through sharing of tutorials, teaching materials and video lessons (Frensley et al., 2017).

The use of online solutions thus complements traditional recruitment methods such as semi-structured telephone interviews, questionnaires and in-person workshops (Davis et al., 2020; Cappa et al., 2020). E-mail, social media campaigns and press releases have long been a full part of recruitment activities in citizen science practices (Arienzo et al., 2021; Frensley et al., 2017; Crall et al., 2017). Such tools are employed to convey web-based surveys (Chase et al., 2018; Church et al., 2019). More advanced recruitment techniques involve the use of mobile phone applications or gaming.

The preliminary considerations given here are to be considered as guidance for setting up and developing citizen science projects of first-hand experience. Such projects will enter advanced stages beyond the time limits of the doctoral research track and constitute research implication to be investigated promoting case studies and best practices at academic and institutional level.

Volunteers' engagement in both case-studies leveraged motivations related to scientific and thematic interest, curiosity, and a sense of community. The possibilities offered by web-based digital technologies prompted setting up recruitment strategies and organizing remote activities to enable more volunteers to take part in the conduct of the case studies. At the same time, the choice allowed for experimentation with remote recruitment techniques for initiating first-hand experience of citizen science in hydrology field. The potential offered by digital technologies combined with motivations related to thematic interests and sense of community prompted to identify groups of university students (cases 1 and 2) and online communities on the topic of meteorology (case 2) as potential volunteers to start communities of citizen scientists active in monitoring and research in the hydrological field.

6.2 Findings and future implications

A summary of findings is here presented related to the research questions stated in the introduction. This section also provides brief implications for research and practitioners.

6.2.1 RQ1: What essential characteristics distinguish citizen science?

The first research question aimed at investigating the definition of models of citizen science to address from transdisciplinary perspectives problematic water sciences.

The research defined an epistemological and conceptual framework to be adopted in the empirical application of citizen science as an organizational and procedural model in the study and monitoring of hydrology and water resources management. This framework is the result of a careful and thoughtful literature review to identify the most common methods, tools, and applications that distinguish citizen science as a distinct scientific research approach.

The multiplicity of perspectives and the complexity given by multidisciplinary implications make citizen science a difficult approach to systematize. Models of citizen science are adaptable and flexible depending on the contexts of application, where social and cultural factors influence engagement, participation but also the design and use of appropriate tools for participatory research and scientific production activities. In this regard, the research work identified four essential points for defining research strategies according to a citizen science approach:

(1) Definition of research questions that intercept collective needs by providing validated scientific solutions with social, environmental, and economic impact. The aims of scientific research must converge on collective needs. Citizen science must offer scientifically valid solutions to social, environmental, and economic problems by making citizens feel an active

part of the solution. The empirical part of the research focused on two exploratory case studies for monitoring and participatory study of hydrological processes. The collective interest lies in the potential implications on risk prevention and sustainable management of water resources.

(2) Identification of target groups that can effectively contribute to the pursuit of scientific goals. Volunteers must provide added value to scientific research by complementing the work of experienced researchers. Citizens represent an extremely diverse group of individuals, each moved to participation by different motivations, interests, and levels of expertise. Therefore, an effective citizen science strategy must be aimed at identifying individuals or groups of people with an interest in the proposed research topic. In the two case studies, volunteers were selected within communities of students, researchers, and weather amateurs to test the established procedures on a sample of citizens motivated by scientific and personal interests.

(3) Definition and adoption of protocols for analysis and validation of observations and data provided by volunteers. Such protocols, where possible, should be agreed upon among experts, citizens, and stakeholders adaptable to the context being analyzed. The shared definition of protocols pertains to advanced citizen science approaches (collaborated, co-created), where the level of citizen involvement and awareness is higher. In the case studies reported here, it was not possible to set up a preliminary dialogue on shared protocols and procedures given their experimental context. Rather, the case studies served as a test for the validity of the methodological procedures adopted. Fixed procedures based on comparative methods-quantitative and qualitative-have been developed to analyze the observations provided by the volunteers, providing promising results on the validity of the observations by comparison with benchmark values provided by experts or traditional monitoring tools.

(4) Continuous interaction between experts and volunteers to share results and incorporate corrective measures, through iterative learning process, in the production of shared knowledge. Volunteer engagement is a continuous and ongoing effort aimed at motivating long-term participation. In this sense, a citizen science strategy must consider tools and procedures for exchanging and sharing feedback and results to instill knowledge, awareness and interest in the citizen.

6.2.2 RQ2: What insights can be grasped for integrating citizen science in organization and management of volunteers?

The second research question aimed to investigate the definition of guidelines and tools for engagement. The adoption of citizen science as research approaches not only involves the establishment of predefined procedures to support the data collection activity but also involves aspects of organizing and managing groups of volunteers. The main insights emerging from this research make it clear that the success (or failure) of citizen science initiatives essentially include two aspects: (1) the validity and quantity of data collected; (2) the active and frequent participation of volunteers. These aspects, in turn, are closely related to the motivations behind people's participation and the (technological) tools adopted. The exploratory and early-stage nature of this study does not allow generalizing findings from the case studies. Rather, the findings that emerged should be interpreted as guiding indications for setting future research implications.

The case studies confirmed the limitations noted in the previous sections regarding the difficulties of starting citizen scientist communities. To cope with this problem, the empirical research activity included several steps for carrying out the tasks required of volunteers, supported by continuous status updates and invitations to contribute further to the research efforts. This communication strategy did not have the expected effects. Participation in research projects remained low (in terms of number of volunteers) and limited (in terms of contributions made). This was mainly due to two limiting factors: (1) the synchronicity of the action; (2) the unpredictability of weather phenomena. In both cases, these were factors beyond the control of the research team and volunteers, as they were strongly influenced by the contingency of events.

The synchronicity of the action depended on the willingness of volunteers to organize workshops (in the first case study) and the occurrence of rain events (in the second case study). These issues necessarily impacted the scheduling and organization of activity phases. The occurrence of precipitation events leads to the second limited point reported above. Therefore, the lack of control over the events impacted the effectiveness of the recruitment communication strategy. The exploratory nature of the case studies led to recruiting groups of volunteers, at times, with small margins of time. This issue did not, however, impact volunteer performance. The results from the activities conducted are promising, confirming the validity of the methodological procedures implemented.

On a hypothetical level, an additional limitation may have depended on the repetitiveness of the tasks and the poor adaptability of the tools used in data collection. Web forms, employed for data collection, are easy-to-use tools because of intuitive graphical interfaces. Conversely, they are non-immediate and automatic tools that made the tasks redundant. These are untested hypotheses but open to further reflection on the implementation of citizen science organizational models around the topic of digital innovation.

Digital technologies are functional to collecting valid and useful data to analyze volunteers' performance in carrying out the activities. The case studies have so far revealed the limits of engagement if not supported by strong motivations and interests of the volunteers. Sharing information and results is the basis around which to build organized communities, where citizens can provide perspectives and viewpoints to guide research, monitoring, and resource management activities. This issue is quite common in the context of citizen science initiatives, where participant motivation and interest notoriously present time-limited effects.

In this sense, the application of citizen science in the field of hydrology is emblematic, especially if it is contextualized in the environmental challenges related to climate change that we are living in these times characterized by the absence of rain and problems related to drought.

Citizen science, on the one hand, offers the tools and possibilities to monitor environmental phenomena related to climate change by evaluating the impacts and daily trends thanks to the volunteered on-field activity. On the other hand, however, the lack of rainfall hinders the activity of volunteers.

Experience brings out some essential points for implementing organizational models in the application of citizen science principles: (1) clarity of objectives; (2) definition of clear roles;

(3) adoption of suitable and user-friendly tools; (4) simple but non-repetitive tasks to stimulate interest (gradual complexity among each activity step); (5) communication campaigns in support of long-term engagement; (6) well-defined time limits. All these aspects vary according to the purpose and capabilities of the volunteers. The effort must be continuous, and the volunteers must have immediate feedback on the work they do. Reward systems can be provided, not in a monetary sense otherwise the voluntary aspect will decay, but in terms of gratification and role within the volunteer community.

The work of estimating water levels in the Montecalvello basin has served to implement citizen science methods for hydrogeological monitoring in marginal contexts. The POP-RAIN project was designed for large-scale rain monitoring. The difference in methodological approach in the two case studies reflects the heterogeneity of citizen science even within a single subject area. This difference also reflects the complexity of hydrology where every single problem (estimation of water levels, rainfall, flows, velocities...) may require different perspectives and methods of study, even adopting citizen science approaches.

Socio-cultural and technological factors influence methodological approaches relating to goals to achieve.

6.2.3 RQ3: How can citizen science (crowdsourcing and participatory approaches) support the advancement of hydrological and socio-environmental sciences?

The third and final research question aimed to investigate the contribution that citizen science can offer in advancements of hydrological and socio-environmental sciences, providing implications for research and practitioners.

Findings from RQ2 already respond in part to RQ3. The research conducted highlighted three aspects regarding the support of citizen science in the advancements of hydrological and socio-environmental sciences. Firstly, citizen science offers innovative organizational and procedural models for addressing water challenges from cross-sectoral and transdisciplinary perspectives. Secondly, the implementation of simple data collection procedures and analytical models highlights how voluntary observations by trained citizens can complement official data. The tests conducted demonstrate the potential contribution of citizens to provide valid data. Main issues are not so much of a technical nature as organizational and cultural. Thirdly, citizen science is a methodological approach useful to co-design and implement technologies suitable for engagement and participatory data collection. This aspect clearly affects the socio-cultural level of the volunteers. The advancement of ICT and digital technologies in daily lives projects volunteer participation in the context of digital transformation, offering new, unexplored sources of data. But the adoption of these technologies is inevitably linked to the level of technological and infrastructural advancement of the context in which it operates. The success (or failure) of citizen science also depends on network coverage and internet access capabilities. It is not by chance that the analysis of the scientific literature reveals a gap in the acquisition of data in rural or non-urbanized areas not effectively covered by the internet. A fundamental aspect considering the necessity and the importance of the monitoring upstream of the hydrogeological phenomena where the lack of data and access to the sites is made difficult by the morphological characteristics.

The design of digital solutions (as in the second POP-RAIN case study) addresses the need to (1) obtain increasingly reliable data for hydrological monitoring; (2) strengthen engagement with a view to continuous and inclusive environmental monitoring. Thus, the research conducted aimed to set the foundation for the implementation of environmental monitoring initiatives with citizen engagement. Having defined the theoretical framework and useful functionalities, future developments concern the engagement strategies to be adopted to extend participation to citizen groups and stakeholders beyond academic context. The application designed within POP-RAIN proposes functionality that can be replicated in different contexts. Technological solution is aimed at identifying social patterns for implementing recruitment to specific targeted groups. Then, the technological solution proposed will guarantee rapid communication and alert systems to maintain high attention and motivations. Rapid communication is also referred to as feedback exchange to create a sense of belonging to a community, making aware citizens on research findings and their role in achievements. Dealing citizens with smartphone app is also aimed to make easier tasks and reducing margin of errors. Finally, digital solutions allow enlarge participation to gather more data. These functionalities are particularly useful in the context of hydrology where monitoring activities are closely dependent on the occurrence of precipitation events.

Another essential factor to scientific advances through citizen science approaches is the support of established organizations and the presence of a strong network of stakeholders to converge toward common goals despite starting from disparate and sometimes conflicting interests. In this sense, research institutions can play a coordinating role among stakeholders, policy makers and citizens toward the shared definition of practices and regulations for monitoring and sustainable management of water resources.

7. Conclusion

In this research work, I investigated the topic of citizen science as an innovative methodological approach to face environmental and hydrological issues according to transdisciplinary perspectives. The major implications of this work are mainly in the realm of academia and scientific research. Despite the vast scientific production on the topic, citizen science has strong experimental and empirical connotations. This research work therefore aims to offer theoretical and practical insights to be tested and applied in conducting participatory and inclusive research activities. First, I focused on defining a theoretical framework for the purpose of reconstructing the relevant semantic field and identifying criteria to deal with citizen science activities in environmental and hydrogeological monitoring. Second, I conducted two case studies to empirically test strengths and weaknesses of citizen science principles identified in the theoretical part. The selected case studies were designed to specifically test citizen science principles within the framework of online interactions.

In the two case studies, I mainly tried to define predefined data collection and validation criteria in order to reduce error margins arising from possible observer bias. The exploratory approach was motivated by the embryonic stages of the case studies. For this reason, my work was aimed primarily at identifying critical aspects and then arriving at criteria that can be replicated in different study contexts. The major contribution of my thesis is to provide theoretical and practical guidelines for starting citizen science activities.

At the theoretical level, I aimed to highlight the distinctive characteristics of citizen science and the tools available in the context of digital transformation by structuring a conceptual framework (Chapter 2). I deepened and contextualized these aspects in the context of online communities and online volunteer interactions as a new frontier of engagement in scientific research activities (Chapter 3). Thus, the theoretical contribution of my thesis offers guidelines for the design of research participatory models based on synergies among experts, stakeholders, institutions and citizens in processes of co-production of knowledge and implementation of new decision-making models, in the sharing of information for the benefit of shared and common solutions to social impact issues.

My further contribution is to provide replicable criteria for initiating, on an empirical level, citizen science activities, based on digital tools and online interactions. In chapters 4 and 5, I described the dual role of citizens as interpreters and observers. In both cases, qualitative characteristics of volunteers can affect the final outcome. The analysis of qualitative aspects of volunteers is necessary in order to identify target groups to be involved in the scientific co-production process. Insights from the two case studies indeed suggest how the qualitative characteristics (background, training) of the volunteers may affect the performance of the results obtained, both in terms of participation over time and in terms of the reliability of the observations.

The research conducted has shed light on the difficulties of maintaining high and stable motivations for volunteers to participate. In this sense, the design of a mobile application (second case study) is a solution to cope with engagement issues. During this research, a prototype was built to support the application based on the limitations that emerged in conducting previous case studies related to monitoring activities. The application is presented as a solution to refine modes of data collection and participation, building on the promising results from the exploratory phases of research. The methodological procedures employed in the initial stages have been shown to be reliable and replicable in other applied research contexts. An explanation of prototype is provided in the Appendix of this thesis.

Citizen science is not limited to data collection and validation. Its implications extend to organizational aspects and the implementation of environmental and social policies, as highlighted in the introduction of this thesis. The work carried out did not dwell on investigating the integration of citizen science into policy but limited itself to investigating its use for scientific purposes. However, the indications that have emerged open to new application threads, shedding light on the need to build stable social networks where academia, institutions and citizens can interact for the purpose of fostering public participation and raising awareness about the social, economic and cultural impacts of citizen science through the definition of agreed and participatory solutions.

The implications of the results of this research concern various areas of scientific research, given the level of flexibility and adaptability of citizen science. In this regard, this thesis has suggested directions for assessing the socio-economic and cultural impacts of citizen science approaches.

One relevant aspect is that citizen science is not limited to being just an innovative approach to scientific research but a method of disseminating awareness and knowledge to people usually uninvolved in decision-making processes based on data-driven strategies.

Under this perspective, the implications of my research extend to the areas of training and education. Indeed, the procedures tested in the two case studies can be replicated to educate groups of citizens within school and professional programs on issues related to environmental sustainability and the fair use of water resources. Finally, further implications may involve the decision-making and governmental sphere at the local level toward the co-definition of policies on the management and implementation of water and environmental services.

8. Appendix. The POP-RAIN app architecture

Sign in/Sign up

When the application is started, the user displays the registration screen. If the user is already registered, they can directly access the application using their credentials. The application handles call to the server. If the user is not registered, they are directed to the registration form. The enrollment form is structured according to the membership model adopted in Phase 2 for online community-based volunteer recruitment. Therefore, to formalize enrollment, the user provides biographical, contact data and qualitative information on educational background based on the scheme shown in table 8.1.

Data_field	**Type**	**Options**
Name and Surname	Text	Short response
Birth date	Date	Set_birth = dd/mm/yyyy
Sex	Multiple choice	• Male • Female
E-mail address	Text	Short response
Degree	Multiple choice	• Primary school • Middle school • High school • Bachelor’s degree • Master’s degree • PhD
Degree course	Multiple choice	• Scientific

		• Technical-scientific • Medical and Health • Humanistic • Law • Economic • Other
Not academic experience in environmental field	Multiple choice	• Yes • No

Table 8.1. Structure of subscription form for citizen scientists engaged in POP-RAIN project.

The inclusion of contact information is functional for future project developments toward establishing an online community active in rainfall monitoring, implementing communication campaigns and alert systems to mobilize volunteers during rainfall events (figure 8.1). The collection of qualitative information is used to monitor each volunteer's performance, monitoring progress and to define user targets. The enrollment form is programmed to automatically accept volunteers aged 18 and older via the set birth equal or greater than 18 function. If the information provided is under 18 years old, the system will activate the alert message that does not allow the enrollment process to be finalized. The compilation of educational background information follows a sequential logic. If the user selects a university degree (bachelor’s degree, master’s degree, or PhD), the "Degree course" container will be unlocked and displayed. If the user indicates YES on environmental expertise, the text container will be activated to enter additional details. Upon completion, the user receives a confirmation and authentication email with a temporary password. The acquired information is thus stored and organized within a relational dataset that links the volunteer's information with his or her subsequent observations.

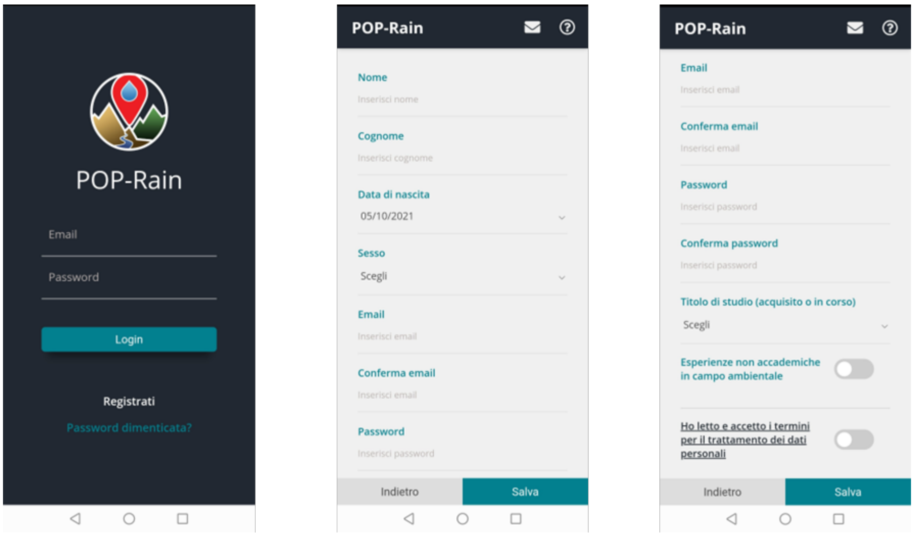


Figure 8.1. Sign up/sign in and registration form screenshots from POP-RAIN app (in Italian).

Main section

Once logged in, the user displays the main screen. From the main screen, the user can navigate to sections of the application or view the list of observations made or saved. The sections of the application are:

- User page
- Observation
- Team
- Project

User section

In the user section (figure 8.2), the user can edit the application settings and their profile. The section presents the following functions:

- Select language: Italian/English.

- Edit profile: redirecting to registration form to change information.
- Edit password.
- Logout.

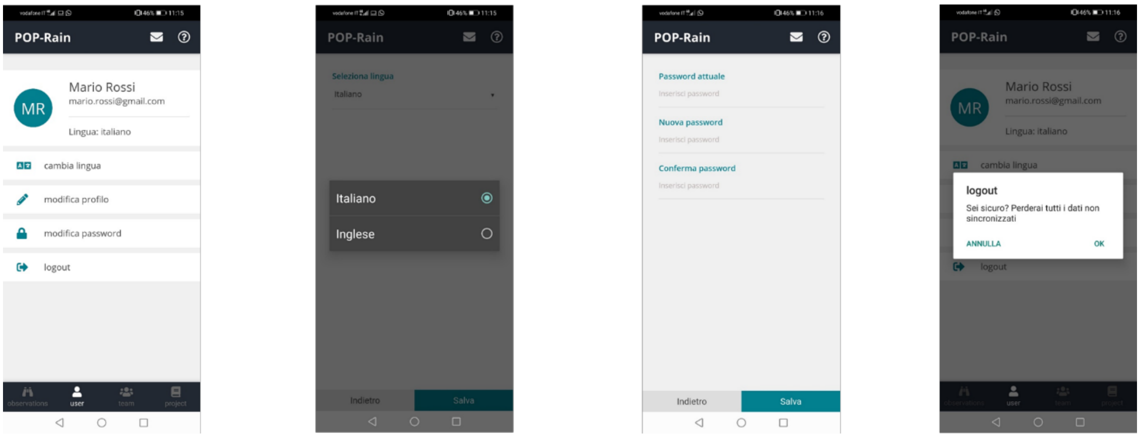


Figure 8.2 . User page screenshots from POP-RAIN app (in Italian).

From this section, the user can change the temporary password received during registration. The user can log out. An alert message will be displayed if the observations made have not been synchronized in the server.

Observation section

In the observations section, the user can record qualitative information about the observed rain event. The observation form is structured according to the scheme shown in the table, echoing the same structure adopted in phase 2 form (table 8.2).

Attribute	**Typology**	**Options**
Observation day and time	Date	Selection from calendar dd/mm/yyyy hh:mm
Duration of observation	Multiple choice	Short integer values

Location	GPS data	• Geographic coordinates (X-value, Y-value) • Elevation (Z-value) • Precision
Previous weather conditions	Multiple choice	• Clear and stable weather • Cloudy weather • Rainy weather
Observation scale	Multiple choice	• Drizzling (<1mm/h) • Very light rain (1-2mm/h) • Light rain (2-4mm/h) • Moderate rain (4-6 mm/h) • Heavy rain (>6 mm/h) • Downpour (>10 mm/h) • Cloudburst (>30 mm/h)

Table 8.2. Structure of observation form for citizen scientists engaged in POP-RAIN project.

Compared with phase 2 form, the data acquisition procedure is made semiautomatic by means of geolocation functions supported by GPS technologies and chronology settings synchronized with the host device settings (figure 8.3). Synchronization with host device functions is instrumental in reducing the margin of error during data collection, often arising from cognitive bias or inadequate knowledge on the part of volunteers as revealed in the critical aspects related to citizen science in the theoretical framework.

The exact location and synchronization of observations facilitate procedures for validating the data by comparison with official rainfall data. Compared with phase 2, where location was based on the volunteer's self-certification, the advantage of GPS technology is that it provides additional information on elevation and accuracy, two aspects that more clearly determine the validity of the data. Activation of GPS on the host device is a necessary condition for observation collection. Failure to activate the GPS does not allow the procedure to be completed. Once the procedure is completed, the observation is stored within the app memory. Finally, the user can choose between synchronizing the observation in the server, editing, or deleting it. By choosing for editing, the user returns to the observation section to edit the attributes of the observation.

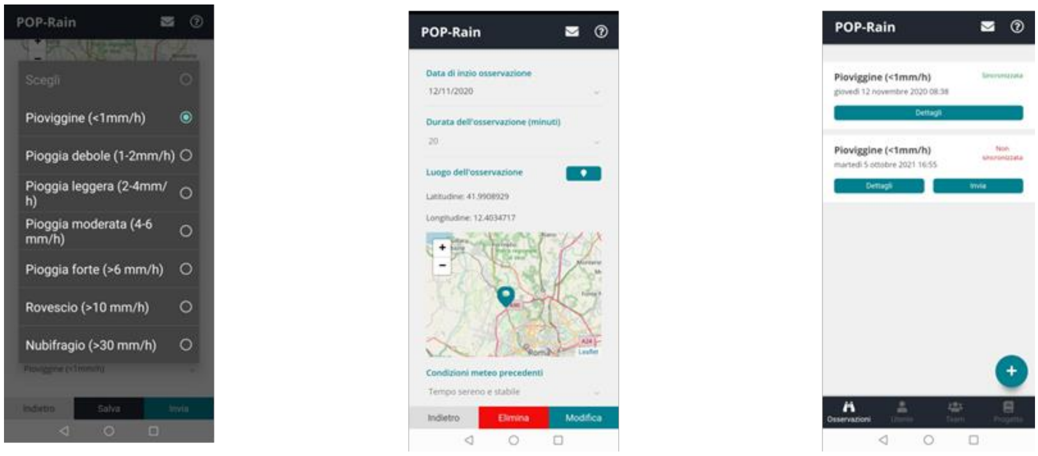


Figure 8.3. Observation section screenshots from POP-RAIN app (in Italian).

Additional sections

Additional sections of the app are:

- Team page, where information on the research team and external links to the university departments involved are reported.
- Project page, where the user consults information about the project and the privacy and data use policy.

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