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Report on best practices on citizen science for the design and monitoring of river restoration projects

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1 Citizen science

Citizen science refers to the engagement of non-professional volunteers in scientific investigations (Miller-Rushing, Primack, & Bonney, 2012). The engagement spans a wide range of disciplines from ecology and astronomy to public health and computer science. It is commonly defined as the involvement of the public in collecting or analysing scientific data in collaboration with professional researchers. The underlying principle is that meaningful scientific contributions can emerge from the collective efforts of individuals without formal scientific training. It has been described as a process in which "volunteers collect and share data that can be analyzed by scientists, project participants, or both" (Cornell Lab of Ornithology, 2013). This definition emphasizes the shared nature of data analysis, highlighting that volunteers can be active partners rather than mere data collectors. In environmental sciences, it is also defined as the "volunteer collection of biodiversity and environmental information which contributes to expanding our knowledge of the natural environment" (Roy et al., 2012). They also enable the detection of ecological trends across temporal and spatial scales that would otherwise remain unobserved. Citizen science is part of a broader framework namely Public Participation in Scientific Research (PPSR), which includes citizen science, stakeholder engagement, public participation, crowdsourcing and other forms of organized research in which members of the public engage in scientific investigations such as answering questions, collecting data and interpreting results (Cornell Lab of Ornithology, 2013; Bonney et al., 2009). Thus, the PPSR umbrella accommodates diverse approaches ranging from contributory data collection to fully participatory research partnerships.

Although public involvement in science has existed for centuries, the modern concept of citizen science has evolved significantly over the last two decades, driven by the development of standardized protocols, digital technologies, and clear scientific objectives (Cohn, 2008; Bonney, 2007). These drivers have facilitated the transition from isolated, small-scale initiatives to coordinated, often global, research networks. This evolution has enabled projects to scale from local observations to continental-level data collection efforts. Moreover, the increasing availability of open-access platforms has allowed project organizers to recruit, train, and manage large volunteer communities more efficiently. The integration of citizens in research investigations is applied particularly in North America, Europe, and Australia (Adler et al., 2020; Chandler et al., 2017). In these regions, institutional support such as funding, infrastructure, and established scientific networks has played a crucial role in fostering citizen science initiatives. Its diffusion is more limited in the Global South (Gurnell et al., 2019; Arraya et al., 2009). This geographic disparity reflects not only technological gaps but also differences in research funding priorities and institutional frameworks. This discrepancy is also due to the impact of the diffusion of new technologies and mobile apps, increasing the possibilities of engagement, transforming people into "citizen sentinel" (Thompson et al., 2014; Goodchild, 2007).

Citizen science projects can be categorized according to the different ways and levels of public involvement in scientific investigations: Contributory, Collaborative, and Co-created (Miller-Rushing et al., 2012; Roy et al., 2012; Bonney et al., 2009). Contributory

projects are designed by professional scientists, with volunteers primarily involved in data collection stage. In such projects, participants typically follow predefined protocols with limited input into research design. This model remains the most widespread due to its relative simplicity and ease of implementation on a large scale. Collaborative projects involve volunteers in additional stages such as analysing data or disseminating results. This approach often benefits from volunteers' local expertise or contextual knowledge during the interpretation of data. By expanding participant involvement beyond data collection, collaborative projects can enhance the accuracy and relevance of research outcomes. Finally, co-created projects involve both scientists and citizens in most steps of the scientific process, including research co-design (Bonney et al., 2009). These co-created models are increasingly recognized for their potential to align scientific outcomes with community priorities and to enhance participant ownership of the research process. Such projects often require longer time frames and more intensive relationship-building, yet they yield benefits in terms of mutual learning and sustained engagement. Collectively, these three categories illustrate a spectrum of public participation, allowing projects to select a model that best aligns with their scientific goals and the capacities of their volunteer communities.

2 Citizen science in River Science and in River Restoration

Citizen science has become particularly relevant for river science (Shao and Bishop, 2025). Its relevance stems from the ability to mobilize large numbers of volunteers who can simultaneously monitor multiple sites across a catchment, generating data at scales that would be prohibitive for research teams alone. Notably, it is particularly helpful in investigating natural and climatic phenomena that are characterized by a large spatial and/or temporal scale (Adler et al., 2020). Indeed, these reasons make citizen science well-suited to capture both short-term disturbance events and long-term ecological trends in river systems. In the UK, 7 out of 26 biodiversity indicators are based on data collected by citizens (Defra, 2012). This integration of citizen-generated data into national indicator frameworks underscores the growing recognition of its reliability and policy relevance.

Rivers require long-term and large environmental monitoring datasets that are often difficult, time-consuming, and expensive to collect using only professional researchers. The logistical challenges of deploying small research teams across extensive river networks often result in data that are sparse in both space and time. Statutory monitoring programmes frequently fail to meet the increasing data demands associated with river restoration initiatives. These programmes are typically designed to meet regulatory compliance rather than to capture the site-specific and multi-year responses that restoration evaluation requires. It was estimated that around 90% of restoration projects in the USA, Australia, and Europe are poorly monitored (Morandi et al., 2014; Bernhardt et al., 2005). This widespread monitoring deficit limits the ability to learn from past restoration efforts and to improve future project designs.

To address this "monitoring gap", volunteers increasingly collaborate with organisations such as environmental agencies, research groups, and NGOs to collect additional environmental data (Gurnell et al., 2019). These collaborations can take various forms, from one-off data collection campaigns to sustained, long-term partnerships between communities and scientific institutions. Monitoring river restoration to detect ecological changes requires large amounts of data collected across both spatial and temporal scales. In fact, to distinguish the ecological effects of river restoration from other influencing factors, a Before–After–Control–Impact (BACI) design is commonly adopted (Huddart et al., 2016). This approach involves conducting field surveys both before and after the intervention, as well as at least one undisturbed site used as a control for comparison. Implementing a BACI design is particularly resource-intensive, as it multiplies the number of sites and sampling occasions required. Citizen science can therefore complement and implement professional monitoring programmes, improving the spatial and temporal coverage of river monitoring, especially when limited resources are available. By distributing monitoring efforts across a broader network of volunteers, citizen science enables the collection of baseline data and control-site observations that would otherwise be unattainable.

Citizen science provides relevant benefits beyond purely technical and scientific outcomes. It can help reduce potential social and political conflicts during restoration projects (Pradhananga et al., 2019; Heldt et al., 2016) and enhance science-public communication regarding the long-term impacts of these interventions (Fraisl et al., 2022; Wehn et al., 2021). When citizens are involved in monitoring, they develop a firsthand understanding of project objectives and the complexity of measuring ecological outcomes. Furthermore, participation in monitoring activities enables citizens to develop a stronger connection with their local environment, enhancing environmental awareness, education, and strengthening their stewardship towards the river ecosystem (von Gönner et al., 2024). This heightened stewardship can translate into sustained community engagement in river management beyond the lifespan of individual restoration projects. Figure 1 summarizes how citizen science in river restoration can address key scientific and social needs, generating multiple benefits.

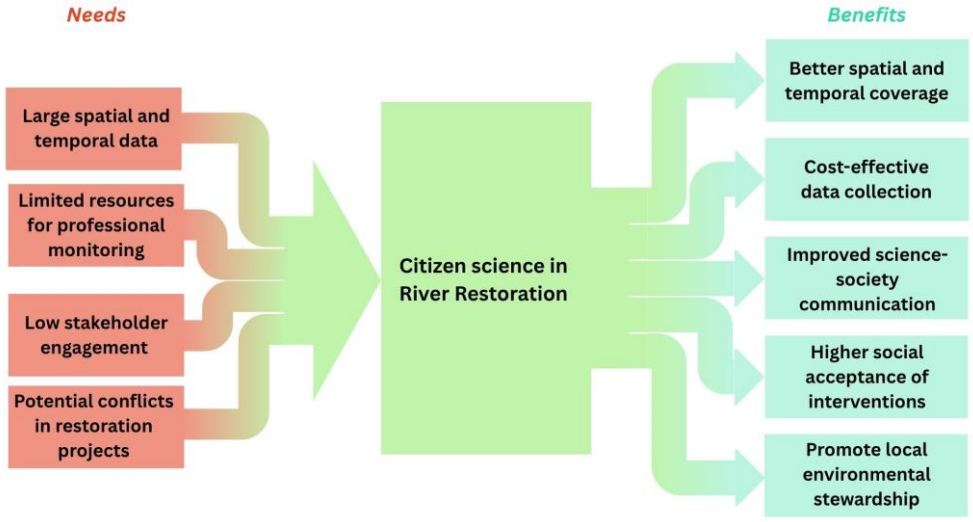

Figure 1. Conceptual framework illustrating the key monitoring challenges citizen science can address in both scientific and societal outputs.

Citizen science projects focusing on rivers typically monitor several environmental characteristics. Monitoring activities can include biological communities, water quality, physical habitat conditions, water levels, and litter accumulation (Gurnell et al., 2019). The choice of which characteristics to monitor often depends on the project's scientific objectives, the training requirements for volunteers, and the availability of standardized protocols. However, most projects focus primarily on biological indicators and water quality, or monitoring pollution, rather than on hydrological data (Hecker et al., 2018; Shao and Bishop, 2025). This focus reflects not only the relative ease of collecting water quality and biological samples but also the high public interest in visible indicators of river health.

One of the most monitored biological indicators is benthic macroinvertebrates. These organisms are widely used in river monitoring because they are sensitive to environmental changes, relatively easy to collect and identify, and widely distributed in freshwater ecosystems (Friberg et al., 2011). Their sensitivity to a broad range of stressors, including pollution, habitat degradation, and flow alteration, makes them effective integrative indicators of overall ecological condition. Changes in macroinvertebrate communities can therefore provide valuable information about water quality and ecological conditions. With appropriate training, volunteers can reliably collect macroinvertebrate samples and, in some projects, perform identification to family level, contributing directly to biological assessment scores.

Water quality monitoring is also common in citizen science initiatives, with a recent study that estimates half of a large-scale water quality database comes from citizen science (Poisson et al., 2020). This substantial contribution demonstrates the capacity of volunteer networks to generate data at scales that complement and, in some cases, exceed those of routine monitoring programmes. Volunteers may collect data on parameters such as turbidity, nutrient levels, or visible pollution indicators. These observations can help identify environmental problems and provide early warning signals of pollution events. The timeliness of citizen-reported pollution events is particularly valuable for triggering rapid responses from regulatory agencies. In addition to biological and chemical monitoring, some projects also assess river habitats, including channel structure, vegetation, and geomorphological characteristics (Huddart et al., 2016; Shuker et al., 2017). Habitat monitoring is particularly relevant in restoration projects because it helps evaluate whether restoration measures are improving ecosystem functioning. Geomorphological monitoring, however, often requires more specialized training and is therefore less commonly undertaken by volunteers, representing a potential area for future methodological development.

3 Best Practices

Successful citizen science initiatives require careful planning and management. Several model programs have been proposed to guide the development of citizen science projects, helping to identify key stages and the main aspects to consider at each step (Fraisl et al., 2022; Bonney et al., 2009). These frameworks provide structured pathways that help project coordinators anticipate challenges and allocate resources effectively across the project lifecycle. All phases should contribute to actively improving the entire project cycle, integrating the lessons learned, and feedback from the community (Fraisl et al.,

2022). The iterative approach ensures that projects evolve in response to both scientific findings and participant experiences. In Figure 2, all stages and corresponding best practices are summarized.

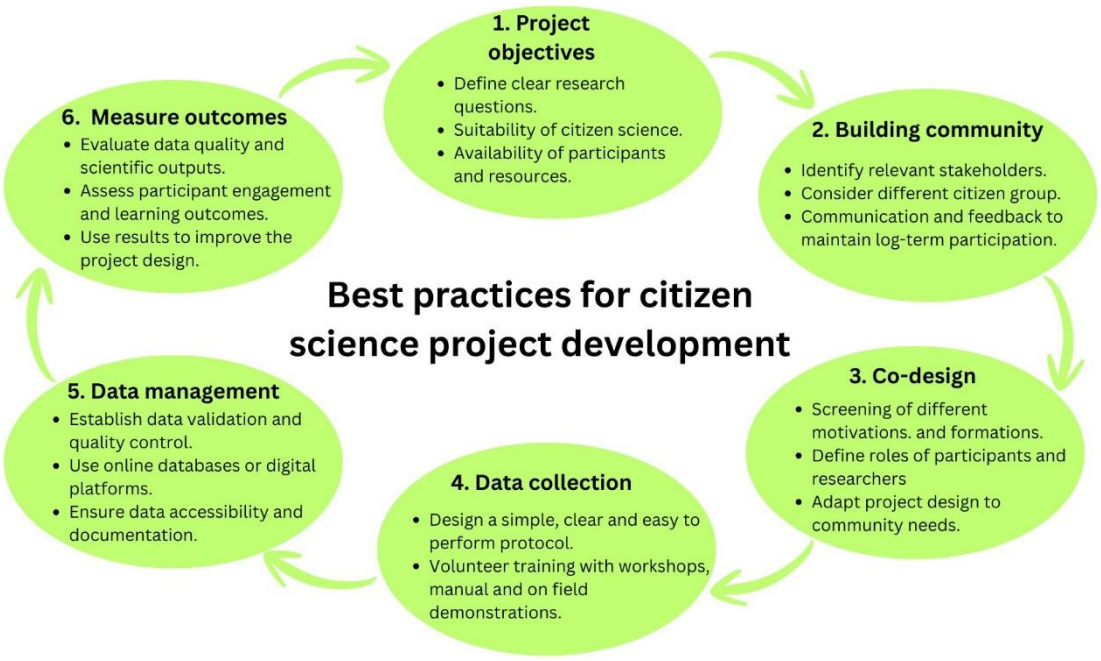

Figure 2. Best practices for each stage of a citizen science project in river restoration.

One of the most important best practices is the clear definition of project objectives and ensuring the suitability of the citizen science method for the scope (Pocock et al., 2014). A mismatch between project goals and the citizen science approach can lead to volunteer dissatisfaction, poor data quality, or failure to achieve scientific outcomes. Citizen science is at its best when research questions are specific and when the purpose is clearly explained to participants (Pocock et al., 2014; Bonney et al., 2009). When volunteers understand how their contributions fit into the broader research context, they are more likely to remain engaged and attentive to protocol details.

The second phase focuses on building a community, identifying the various stakeholders involved in the restoration project and the community groups that might be involved, as well as tailoring the communication to each of them. Effective community building requires mapping not only formal stakeholder organizations but also informal networks such as resident groups, angling clubs, and schools that may have longstanding connections to the river. Marginalised communities are frequently underrepresented in citizen science projects due to social barriers (Levine et al., 2009; Trumbull et al., 2000). These barriers can include language differences, limited access to transportation, historical mistrust of research institutions, or competing time demands from work and family responsibilities. Participatory approaches and targeted communication strategies that engage different groups within the community can help build trust and foster more inclusive participation (Adler et al., 2020; Pandya, 2012; Jolly, 2002). Engagement with participants is also essential (Pocock et al., 2014). Projects that prioritise continuous communication, feedback, and collaboration with volunteers are more likely to achieve both scientific and social goals (Feio et al., 2021; Adler et al., 2020; Pocock et al., 2014).

Building engagement is not a one-time event; it requires sustained effort throughout the project duration. Providing regular updates and showing how collected data are used can help maintain motivation and participation. When volunteers see tangible evidence that their efforts contribute to real-world outcomes, their sense of purpose and commitment is reinforced.

Stage 3 corresponds to the design phase in "Contributory" and "Collaborative" citizen science projects, while in "Co-design" approaches, this stage involves the joint development of the project by both researchers and participants. In this approach, experts and volunteers are involved from the early stages of the project, combining scientific expertise with local and holistic knowledge to shape the project structure and monitoring protocols (Bonney et al., 2009). Co-design processes are time-consuming upfront, but can yield projects that are better adapted to local contexts and more resilient to unforeseen challenges. Co-design approaches can be particularly useful in remote areas, regions with limited technological infrastructure, or communities with low access to digital tools (Vos, 2024). In such settings, co-design helps ensure that monitoring methods are feasible given local conditions and resources.

Furthermore, involving local communities in the design of research questions, monitoring protocols, and data management can help recognise and integrate local knowledge, transforming participants from simple data collectors into active contributors to scientific knowledge. (Pandya, 2012). This transformation often leads to a deeper commitment from volunteers and a greater sense of ownership over project outcomes.

Moreover, volunteers participate in citizen science for a variety of reasons. Some individuals are motivated by the opportunity to contribute to scientific research, while others are interested in learning about nature or engaging in community activities. Still others may be driven by personal connections to a specific river site, concerns about local environmental issues, or the social aspects of participating in a group activity. Understanding these motivations is important for maintaining long-term participation (Geoghegan et al., 2016; Kragh et al., 2016; Pocock et al., 2014). Recognizing that motivations can shift over time, projects should offer multiple pathways for engagement that accommodate different interests and availability levels. Providing feedback and recognising volunteer contributions can help retain participants and sustain engagement over time. When volunteers see how their data contributes to environmental research or policy decisions, they are more likely to remain involved in the project. Recognition can take many forms, from informal acknowledgements in newsletters to co-authorship opportunities on scientific publications where appropriate.

Another key element is the design of data collection protocols. Protocols should be simple, clearly explained, and easy to perform (Bonney et al., 2009). Excessive complexity can lead to participant frustration, increased error rates, and higher volunteer attrition. Complex methods may discourage participation and reduce data reliability. Therefore, data forms and monitoring procedures should be designed to be simple and accessible for volunteers, reducing the likelihood of errors when recording essential data during field surveys (Blake, 2025). Pilot testing protocols with a small group of volunteers before full implementation can help identify ambiguities or practical difficulties that may not be apparent to professional researchers. Volunteer training is fundamental for the success of citizen science projects (Adler et al., 2020; Dickinson et al., 2010). Workshops,

manuals, field demonstrations, and online resources can help volunteers understand monitoring protocols and improve the quality of collected data. Often, a combination of training methods works best, accommodating different learning styles and providing multiple opportunities for skill development. Providing clear instructions and ongoing support helps ensure that data is collected consistently and accurately (Theobald et al., 2015; Roy et al., 2012; Gardiner et al., 2012). Training programmes help participants understand monitoring protocols and develop confidence in their data-collection skills. Confident volunteers are more likely to participate consistently and to take on leadership roles within the project.

Furthermore, teamwork should be encouraged because peer-to-peer supervision between volunteers can significantly increase the quality of data recorded, achieving a level of accuracy comparable to that of experts (Swanson et al., 2015; Crall et al., 2011; Bonney et al., 2009). Pairing new volunteers with more experienced participants creates informal learning opportunities and distributes the responsibility for quality assurance across the volunteer community.

Citizen science projects should include systems for data management and quality control. Online forms can enable a filtering step, through which anomalies can be flagged before entering into the database (Bonney et al., 2009). Automated flagging rules based on expected value ranges can catch common entry errors at the point of submission, reducing the burden of post-hoc data cleaning. Moreover, online databases, digital platforms, and validation procedures can help verify data and make it accessible to both scientists and participants. Transparent data management practices, where volunteers can see how their submissions are processed and validated, build trust and demonstrate the value placed on their contributions. New technologies, such as smartphones and design apps equipped with integrated online modules and a structure that enables data to be stored, validated, and processed, offer great potential for integrating and improving both the data collection and data management phases (Newman et al., 2012). Smartphones, which are now "networked mobile personal measurement instruments" (Paulos et al. 2008; Wobbrock 2006), can enhance data collection and management with the built-in availability of metadata, such as location and real-time mapping services (Lwin and Muryama 2011). This automatic capture of contextual information reduces the cognitive load on volunteers and minimizes transcription errors. Furthermore, they can stimulate real-time dialogue between scientists and volunteers (Newman et al., 2012). Such dialogue enables rapid clarification of protocol questions, immediate feedback on data quality, and the cultivation of a more interactive and responsive project community.

The final stage focuses on evaluating and disseminating the outcomes of the citizen science project. Disseminating results through reports, public events, and digital platforms helps communicate project findings to participants, stakeholders, and the wider community (Bonney et al., 2009). Closing the feedback loop by sharing results with volunteers is not merely a courtesy but a critical element of sustaining trust and motivation for future initiatives. Evaluation can also explore how participation influences volunteers' perceptions and relationships with the river, for example, by increasing environmental awareness, sense of stewardship, and connection with local ecosystems (Eitzel et al., 2023; Smith et al., 2016). These social and affective outcomes, while more difficult to quantify than scientific outputs, are often as important for the long-term success of citizen science initiatives. These insights can help improve future citizen

science initiatives and strengthen the long-term impact of monitoring programmes (Huddart et al., 2016). Systematic evaluation, including lessons learned from challenges and setbacks, contributes to a growing body of practical knowledge that benefits the wider citizen science community.

Several citizen science initiatives have been applied to river restoration, demonstrating both the potential and the limitations of these approaches. The list of case studies and projects reported in Table 1 illustrates how citizen science can be tailored into a variety of contexts, from small-scale local projects to large, coordinated monitoring networks. Collectively, they provide valuable insights into the practical challenges of implementation, the trade-offs between simplicity and scientific rigor, and the conditions under which volunteer-based monitoring can effectively complement or even substitute for professional data collection.

Table 1. List of citizen science initiatives applied in river restoration emphasizing best practices and limitations.

Case study / Project	Year	Purpose	Strengths	Limitations
ARMI - Riverfly Partnership (BES, 2014)	2014	Monitor water quality using macroinvertebrates	- Simple and replicable method - Standardized monitoring protocol - Provides early warning of pollution events - Large volunteer network	- Less detailed than professional monitoring - Limited to biological indicators - Requires a significant upgrade in training to be applied in restoration activities (protocol Riverfly Plus)
Salmon Creek (**Woelfle-Erskine**, 2017)	2017	Support watershed management through collaborative monitoring in intermittent salmon-bearing streams	- Integration of local and scientific knowledge - Supports governance processes in water re-allocation	- Limited inclusion of marginalized groups -Limited standardisation of data collection
Rock Creek (Edwards et **al.**, 2018)	2017	Monitor the improvement of salmon-rearing habitat through native riparian plantings	- Robust BACI design - Long-term dataset (7 years) - 2300 students involved	- Absence of co-design stage - No evaluation of social benefits

Chalk streams (Beach et al., 2018**)**	2018	Integrate biological (Riverfly) and habitat (MoRPh Survey) monitoring	- Integrated biological and physical habitat monitoring approach - Useful data for management	- Limited taxa monitored in the Riverfly survey - Limited spatial scale investigated
The Green Partnership - Øle Å River (Gamborg et al., 2019)	2019	Facilitate adaptive restoration through stakeholder involvement	- Improves trust and mutual understanding - Enables adaptive management and cooperation in ecological restoration	- Time-intensive process - High coordination requirements
Marzenego River (application of Ground Truth 2.0 and MICS frameworks)	2020	Integrate citizen science into river restoration through citizen observatories and structured impact evaluation	- Combines citizen observatory approach (Ground Truth 2.0) with impact assessment framework (MICS) - Strong science–policy integration improving the existing Marzenego River Contract - Participatory co-design process - Comprehensive evaluation of environmental and social impacts	- High organizational complexity - Requires strong coordination among stakeholders
Zenpukuji River (Takizawa et al., 2020**)**	2020	Engage communities in planning river restoration	- Strong community–science integration - Participatory design - Multi-stakeholder involvement	- Engagement only in the design stage, no volunteers involved in data collection

Thames Rivers Trusts – Thames Catchment	2022	Support eel conservation and river restoration by identifying barriers to migration and monitoring eel populations	- Citizen science used to map and assess barriers (ObstacEELS) - Combines ecological monitoring with community engagement	- Limit involvement in design stage - Limited temporal scale for data collection
Magdalena River Restoration Project **(**Garciadiego et al., 2023)	2023	Analyze community participation in restoration governance	- Highlights social barriers - Provides critical perspective on participation	- Weak community integration - Social inequalities - Limited success in engagement
Elwha River (Eitzel et al., 2023)	2023	Support monitoring and governance in dam removal project	- Strong community–science integration - Engagement of tribal communities - Participatory design - High social benefits - Large spatial scale analysis	- Highly skilled participants necessary -Numerous volunteers needed - Ongoing volunteer engagement
MoRPh (Modular River Physical survey) **(Shuker et al.**, 2024**)**	2024	Monitor hydromorphological conditions and restoration outcomes	- Low-cost and standardized monitoring - Applicable at small and large spatial scales - Enables temporal analyses (BACI design)	- Focused mainly on physical aspects - Requires basic training - Limited spatial coverage in individual studies
Muddy River (**Akingbile et al.**, 2024)	2024	Development of an accessible method to collect geomorphological data to inform restoration planning and to	- Low-cost and accessible tools - Enhances community engagement	- Limited period to work on field with volunteers and collect large amount of data

		expand community engagement	- Supports data collection in data-poor contexts	
Llegim el riu, Catalonia (Fortuño et al., 2025)	2025	Promote participatory river assessment through community-based approaches	- Co-creation approach - Supports decision-making - Innovative use of public institutions like public libraries to reach different groups of people - Creation of long-term community groups supporting restoration activities	- Project support decision-making, not direct actions of restoration - Data collection focused more on qualitative and semi-quantitative data on river condition
Rattlesnake Creek (Blakey, 2025**)**	2025	Assess ecological and geomorphological impacts of dam removal	- Integration of biological, chemical, and geomorphological data - Educational engagement (Stream Team) - Long-term dataset (7 years) - BACI design	-Macroinvertebrates monitored through a water quality index (WAV Biotic Index) -Multiple errors in gathering cross-section data from volunteers

Across these diverse case studies, several common themes emerge regarding the factors that contribute to successful citizen science in river restoration. Projects that combine multiple monitoring methods—such as biological and physical habitat assessments—tend to provide a more comprehensive picture of restoration outcomes than those relying on a single indicator. Furthermore, initiatives that embed citizen science within existing governance structures, such as River Contracts or participatory observatories, appear better positioned to translate volunteer-collected data into tangible management decisions. Conversely, the limitations documented in these case studies highlight persistent challenges related to volunteer training requirements, data quality assurance, and the need for sustained coordination efforts over multi-year timescales.

4 Examples of operational frameworks

Beyond individual case studies, a number of well-established frameworks have been developed to support citizen science across its full project lifecycle, from co-design (Ground Truth 2.0) and data collection (ARMI and MoRPh) to impact evaluation (MICS).

1. GroundTruth 2.0

The Ground Truth 2.0 co-design methodology is a participatory approach developed to support the creation of Citizen Observatories (COs) for environmental monitoring and governance (Wehn and Pfeiffer, 2020). Citizen Observatories represent an evolution from traditional citizen science by embedding volunteer monitoring within formal governance frameworks, thereby creating structured pathways for data to inform policy and decision-making. COs are collaborative systems in which citizens, scientists, policymakers, and other stakeholders jointly collect, share, and use environmental data to address local challenges. The underlying premise is to give a meaningful role to those affected by environmental decisions in generating the knowledge that influences those decisions.

The method follows the Living Lab principles, emphasizing real-world experimentation, user participation, and collaboration among diverse actors. Living Labs are characterized by their focus on co-creation, where innovation emerges through iterative cycles of testing and refinement in authentic settings rather than through top-down implementation. A key feature is the co-design process, in which stakeholders participate from the earliest stages to collectively define the environmental problem, the scope of the observatory, and the functionalities required for the technological platform. This early involvement helps ensure that the resulting tools and protocols are not only scientifically sound but also practically relevant and socially acceptable to the communities that will use them. Citizens are not limited to data collection but can contribute to all stages of knowledge production, including problem framing, data analysis, and interpretation. By expanding the roles available to participants, the Ground Truth 2.0 approach seeks to move beyond transactional models of volunteer engagement toward more collaborative and empowering forms of participation.

The methodology is structured into five main phases. The first phase focuses on process planning, including context analysis and stakeholder identification. This initial scoping phase is critical for understanding the socio-political landscape within which the observatory will operate, including existing power dynamics, prior levels of trust between stakeholders, and the availability of complementary data sources. The second phase involves social innovation design, where stakeholders develop a shared vision, objectives, and functional requirements for the observatory. At this stage, participants define the scope of the observatory's activities, balancing scientific ambitions with practical constraints, such as the availability of volunteers and resources. The third phase concerns tool development and launch, during which the technological platform and interfaces are designed and implemented. User-centered design principles are applied to ensure that digital tools are intuitive and accessible to participants with varying levels of technological familiarity. The fourth phase focuses on community mobilization and implementation of activities, such as data collection campaigns and stakeholder engagement initiatives. This phase often requires dedicated community management efforts to sustain momentum, recruit new participants, and maintain data quality

standards. Finally, the fifth phase supports the long-term operation and evolution of the observatory, ensuring sustainability through governance structures, platform maintenance, and continuous community participation. Securing long-term sustainability remains a persistent challenge for Citizen Observatories, as initial project funding typically covers only the development and early implementation phases.

The Ground Truth 2.0 methodology has already been applied in the context of citizen science in river science during the MICS project for the Marzenego river restoration (Gumiero et al., 2020). This application demonstrated both the potential of co-designed observatories to strengthen science-policy interfaces and the substantial coordination demands that such approaches entail.

2. ARMI (Anglers' Riverfly Monitoring Initiative)

The Anglers' Riverfly Monitoring Initiative (ARMI) is a well-known example of citizen science applied to river monitoring (Brooks et al., 2019). It was developed in the United Kingdom in the early 2000s in response to concerns from the angling community about declining water quality and the limitations of official monitoring programmes in detecting pollution events promptly. In this method, trained volunteers collect macroinvertebrate samples using a standardized sampling net and identify a set of 8 easily recognisable taxa that are sensitive to pollution. These eight taxa—which include mayflies, stoneflies, and caddisflies—were selected because they are sufficiently sensitive to pollution to serve as early warning indicators while still being identifiable by volunteers after a single day of training. Volunteers usually monitor sites monthly, providing more frequent monitoring than many official programmes. This temporal resolution is particularly valuable for detecting acute pollution events that might be missed by less frequent statutory monitoring.

Before taking part in fieldwork, volunteers must attend a one-day training workshop led by accredited instructors (https://www.riverflies.org/set-up-a-group). The training combines classroom instruction on the identification of macroinvertebrates with practical field sessions in which participants practise sampling techniques under supervision. These workshops ensure that participants understand the monitoring protocol and can correctly identify the target organisms. Following initial training, volunteers are typically required to pass a proficiency test to confirm their identification skills before they begin independent monitoring. This quality assurance step is essential for maintaining data reliability across the network, which now comprises over 4,000 trained volunteers operating at more than 2,000 sites across the UK.

Furthermore, a specific protocol, namely Riverfly Plus, was designed specifically to investigate the impacts of river restorations. It is used with the ARMI basic method to detect before-and-after responses of the biota. The development of Riverfly Plus reflects a recognition that while the basic ARMI method is effective for detecting pollution incidents, its eight-taxa approach lacks the taxonomic resolution needed to detect more subtle ecological changes associated with habitat restoration. The methodology increases the number of taxa that must be identified to achieve more nuanced monitoring. To accomplish this, volunteers must attend a more extensive training course that provides them with the skills to recognize 33 taxa and additional species (Brooks et al., 2019). This extended training requires a greater investment of time from both volunteers and

instructors, and consequently, the Riverfly Plus protocol has been adopted by a smaller but highly dedicated subset of the overall ARMI volunteer base. The availability of two distinct protocols within the same programme illustrates an important principle in citizen science design: offering tiered levels of engagement can accommodate volunteers with different capacities and interests, allowing projects to balance breadth of participation with depth of data quality.

3. MoRPh (Modular River Survey)

Another example is the Modular River Survey (MoRPh). This monitoring tool allows citizen scientists to assess the geomorphological properties and habitat characteristics of rivers (Shuker et al., 2017). It was developed in response to the recognition that while biological monitoring is well represented in citizen science, physical habitat assessments remain largely the domain of professional practitioners, creating a significant gap in the data available to inform river management and restoration evaluation. Thus, it is useful for understanding the evolution of river morphodynamics, aligning with the spatial scale of biological monitoring, aiding in the detection of morphological degradation, and assessing the success of river restoration measures by enabling volunteers to document features such as bank erosion, sediment deposition, channel modification, and riparian vegetation structure (Shuker et al., 2017; Huddart et al., 2016). MoRPh provides a structured approach to capturing physical habitat data that would otherwise be prohibitively resource-intensive for professional teams to collect across large spatial scales. Originally, it was designed to complement Riverfly but can be easily adapted to different monitoring projects (Gurnell et al., 2019). The complementarity between MoRPh and Riverfly is particularly valuable because it allows volunteers to collect both biological and physical data at the same locations, facilitating integrated assessments of river condition. One day of online training is necessary to become a surveyor (https://modularriversurvey.org/). The online format of the training has significantly lowered barriers to participation, enabling volunteers across geographically dispersed areas to gain certification without the need for in-person workshops.

MoRPh is particularly valuable because many citizen science projects focus mainly on biological monitoring, leaving physical habitat assessments less explored. This gap is significant because biological conditions in rivers are shaped by physical habitat structure, and restoration interventions often target physical modifications such as bank reprofiling, gravel addition, or large wood placement. A rigorous protocol helps citizens in the spatial exploration of the river, guiding them on which aspects to regard (Gurnell et al., 2019; Shuker et al., 2017). The protocol includes detailed guidance and photographic examples to help volunteers consistently interpret and record river features, reducing inter-observer variability and enhancing data comparability across sites and surveyors. The MoRPh tool trains volunteers in recording physical characteristics of the riverbed, banks, and up to 10m from the active channel, while also taking riparian habitats into account. This extended buffer acknowledges that riparian zones play a critical role in regulating light, temperature, and organic matter inputs to the river, and that restoration of physical habitat often requires consideration of land adjacent to the active channel.

The MoRPh survey can be applied at three different spatial scales. The smallest scale is around two times channel width in length, called “module”, to monitor habitats comparable to a macroinvertebrate site (mesoscale). This alignment with the spatial scale of biological sampling allows for direct comparisons between physical habitat conditions

and biological communities. Combining ten consecutive MoRPh modules, reaching subreach scale, MultiMoRPh surveys the capture of physical habitat dynamics for larger and more dynamic species, such as fish. The subreach scale is particularly relevant for assessing habitat heterogeneity, which is a key indicator of ecological quality and a common target of restoration interventions. The HydroMoRPh survey can expand the spatial scale to the reach scale, using remote sensing and open-access data. This multi-scale architecture is one of the MoRPh system's distinctive strengths, as it allows projects to tailor the level of monitoring effort to their specific research questions and available volunteer capacity, while maintaining methodological consistency across scales.

4. MICS (Measuring Impact of Citizen Science)

MICS (Measuring Impact of Citizen Science) is a Horizon 2020 project launched in 2020 to develop an Impact Assessment Framework, including tools and metrics, to systematically evaluate the impacts of citizen science initiatives across five key domains: society, science and technology, environment, economy, and governance (Gumiero et al., 2020). The project was motivated by the observation that while citizen science projects frequently claim to generate diverse benefits beyond scientific data—such as enhanced environmental awareness, policy influence, or community empowerment—these impacts are rarely systematically documented or quantified. The main outcome of the project is the Citizen Science Impact Assessment Framework (CSIAF), which provides a structured yet flexible approach to capturing and comparing the diverse impacts of citizen science projects (Wehn et al., 2021). The CSIAF is designed to accommodate the wide variation in project types, scales, and contexts, recognizing that a one-size-fits-all approach to impact assessment would be both impractical and inappropriate.

The CSIAF was developed in response to the lack of standardized methodologies and the fragmentation of existing approaches, which often focus on only a limited number of impact domains. Before the advent of MICS, impact assessments in the field of citizen science were usually carried out on an ad hoc basis, limited to individual projects and disproportionately focused on scientific outputs, such as publications and datasets, whilst much less attention was paid to social, governance, or economic outcomes. It enables a more consistent and comparable evaluation of outcomes across projects, while acknowledging the complexity and non-linearity of impact pathways, where changes in one domain (e.g., society or governance) may precede environmental improvements. For example, a citizen science project might first build social capital and trust among stakeholders, which then enables more collaborative decision-making, which in turn leads to more effective restoration interventions and eventual environmental improvements, a chain of causality that would be missed by assessments focused solely on environmental metrics.

Empirical evidence collected within the MICS project highlights that impact assessment is often not performed due to its perceived complexity, time requirements, and limited resources or expertise among project coordinators. Many citizen science projects are led by researchers or practitioners whose primary expertise lies in environmental science or community engagement rather than in evaluation methodologies, creating a practical barrier to rigorous impact assessment. As a result, when conducted, it is frequently partial or insufficient. To address these barriers, MICS developed an online platform (https://about.mics.tools/guidance/measure/mics-platform) that provides an accessible entry point into impact assessment. This lack of systematic evaluation creates a feedback

gap: without evidence of what works and what does not, the citizen science community struggles to learn from past experiences and to make the case for sustained investment in these approaches. The platform enables the evaluation of citizen science initiatives at any stage of implementation through a structured set of over 200 questions with predefined answers. By offering a standardized yet customizable assessment tool, the platform lowers the technical barriers to impact evaluation and enables projects to generate comparable data that can contribute to a growing evidence base on the effectiveness of citizen science across different contexts. These questions cover a wide range of indicators derived from existing frameworks and are analysed through AI algorithms to generate impact scores across the five domains. The use of AI algorithms enables more efficient processing of complex, multicriteria evaluation data, providing project coordinators with useful information without them having to become experts in evaluation methodologies. The MICS framework and its associated tools represent an important step toward professionalizing impact assessment in citizen science, enabling the field to move beyond anecdotal claims of success toward an empirically grounded understanding of when, how, and under what conditions citizen science generates its diverse benefits.

5. Future Challenges

Despite its many advantages, citizen science also faces several future challenges. The future challenges span technical, organizational, social, and institutional dimensions, and their relative importance varies considerably across different project contexts, geographic settings, and stages of project development. Recognizing and proactively addressing possible limitations is essential not only for improving individual project outcomes but also for advancing the broader credibility and impact of citizen science as a research approach.

One of the main concerns is data quality (Bonney et al., 2009). This concern is perhaps the most frequently cited barrier to the adoption of citizen science data by professional researchers, environmental agencies, and policymakers, who may perceive volunteer-collected data as inherently less reliable than data gathered by trained scientists. Because volunteers have different levels of expertise, inconsistencies or errors in data collection may occur (Blake, 2025). These errors can take various forms, including misidentification of species, inaccurate measurement of physical parameters, inconsistent application of sampling protocols, or omissions in data recording. The potential for such errors is heightened in projects with high volunteer turnover, where new participants must be continuously trained and brought up to a consistent standard. A clear scope from the beginning helps in defining the best trade-off between data quantity and data quality, especially in citizen science activities (Huddart et al., 2016). This trade-off is inherent to the citizen science model: projects that prioritize broad participation and large volumes of data may need to accept some degree of variability in data quality, while projects that demand high precision may need to restrict participation to volunteers who can commit to extensive training and ongoing quality assurance. Striking the right balance requires careful consideration of the scientific questions being asked, the level of accuracy needed

to answer them, and the capacities and motivations of the available volunteer pool. To address this, the implementation of appropriate quality assurance (QA) and quality control (QC) protocols is essential. However, research shows that with appropriate training and standardized protocols, citizen scientists can collect reliable data comparable to that collected by professionals (Roy et al., 2012; Gardiner et al., 2012; Theobald et al., 2015). Studies comparing volunteer-collected data with professional benchmarks have found that, particularly for well-designed protocols with robust quality assurance mechanisms, the accuracy of citizen scientists can match or even exceed that of professionals, especially when volunteers are highly motivated and deeply familiar with their local monitoring sites. Nevertheless, achieving this level of reliability requires sustained investment in training infrastructure, protocol development, and quality control systems—investments that may be difficult to sustain in projects with limited resources or short time horizons.

Beyond data quality, another significant challenge relates to the representativeness and inclusivity of citizen science participation. Evidence from multiple studies indicates that citizen science volunteers tend to be disproportionately drawn from certain demographic groups—often individuals with higher levels of formal education, higher disposable income, and more flexible schedules (Pandya, 2012). This homogeneity can limit the diversity of perspectives informing research questions and can result in monitoring efforts that reflect the priorities and access of privileged groups rather than the full range of communities connected to a river landscape. Furthermore, volunteer participation often exhibits spatial biases, with monitoring sites concentrated near urban centers or locations that are easily accessible by car, leaving remote or less visible river reaches undersampled. Addressing these biases requires intentional outreach strategies, partnerships with community-based organizations, and the removal of practical barriers such as transportation costs, language accessibility, and time demands that may disproportionately affect marginalized populations.

Citizen science projects may also face organisational challenges such as limited funding, lack of coordination, or insufficient technical infrastructure. Funding constraints are particularly acute because citizen science projects often require sustained support over many years to build volunteer networks, maintain training programs, and generate the long-term datasets necessary for detecting ecological trends. However, they are frequently funded through short-term research grants that do not accommodate the extended timelines of community-based monitoring. The lack of coordination can manifest in various ways, including fragmentation across projects working on the same river systems without mechanisms for data sharing or methodological alignment, duplication of efforts, and missed opportunities for cross-project learning and synthesis. In some regions, poor digital infrastructure leads to limited access to technology and internet connectivity, restricting participation. This digital divide is especially pronounced in rural areas, where river restoration projects are often located, as well as in economically disadvantaged communities and in many parts of the Global

South, where ecosystems are often more vulnerable to climate change due to socio-economic and environmental factors. The increasing reliance on smartphone applications, online training platforms, and cloud-based data management systems, while offering many benefits in terms of data standardization and real-time feedback, can inadvertently exclude individuals and communities without reliable access to these technologies. Projects that assume universal digital literacy or connectivity risk perpetuating existing inequities in who can participate in and benefit from citizen science.

Another important limitation concerns the integration of citizen science data into formal decision-making processes. Even when data quality is high, regulatory agencies and water management authorities may be reluctant to incorporate volunteer-collected information into statutory monitoring frameworks, citing concerns about legal defensibility, methodological consistency with established protocols, or the absence of clear mechanisms for data validation and certification. This institutional resistance can limit the policy impact of citizen science and diminish volunteer motivation when participants perceive that their efforts do not translate into tangible management outcomes. Overcoming this barrier requires not only robust data quality systems but also sustained engagement with decision-makers from project inception to build trust, align monitoring objectives with regulatory needs, and develop formal pathways for data uptake.

Despite these institutional barriers, citizen science continues to grow as a valuable approach for environmental monitoring and river restoration (Gurnell et al., 2019; Silverton et al., 2009). This growth is reflected in the increasing number of published studies drawing on citizen science data, the proliferation of national and international citizen science networks, and the recognition of citizen science in policy documents ranging from the European Union's environmental action programs to national biodiversity strategies. The trajectory of growth suggests that citizen science is transitioning from a niche activity conducted by passionate enthusiasts to a more mainstream component of environmental research and management, with expanding expectations for its contribution to monitoring, evaluation, and public engagement. Combining scientific expertise with community participation, it provides an inclusive and collaborative way to address environmental challenges. The integration of public participation and citizen science represents a key future challenge, with the potential to enhance citizen engagement in ecological restoration projects (Kang et al., 2022). This combination is particularly powerful in this context, where ecological processes unfold across spatial scales that exceed the capacity of professional monitoring alone, and where community support and stewardship are critical for the long-term success and maintenance of restoration interventions.

Looking ahead, several interrelated challenges will shape the evolution of citizen science in river restoration over the coming decade. First, there is a pressing need to move beyond pilot projects and short-term initiatives toward sustained, institutionalized monitoring programs that can generate the multi-decadal datasets needed to evaluate restoration

outcomes in the context of climate change and other long-term environmental trends. Second, the field must grapple with questions of scalability: how to maintain data quality, volunteer motivation, and community engagement as projects expand from local to catchment or national scales. Third, as the volume of citizen science data grows exponentially, new challenges emerge around data management, interoperability across different platforms and protocols, and the development of analytical approaches capable of extracting robust ecological signals from heterogeneous, multi-source datasets.

A further future challenge concerns the integration of citizen science with emerging technologies, including artificial intelligence and machine learning. While these technologies offer exciting possibilities for automated species identification, real-time data validation, and intelligent feedback to volunteers, they also raise questions about the balance between automation and human engagement. If algorithms assume tasks that were previously performed by volunteers—such as species identification or anomaly detection—there is a risk that participants may become disconnected from the interpretive aspects of monitoring, potentially diminishing the educational and stewardship benefits that are among the most valued outcomes of citizen science. Conversely, when thoughtfully designed, human-AI collaboration can enhance both data quality and volunteer learning, allowing participants to focus on higher-level tasks while benefiting from algorithmic support for routine or complex identification work.

Finally, the future of citizen science in river restoration will depend significantly on the development of sustainable funding and governance models. Many of the most successful citizen science initiatives have relied on a combination of public funding, philanthropic support, and in-kind contributions from volunteers, universities, and NGOs. However, this patchwork of support is often precarious, and projects may face existential threats when key funding sources expire or when key individuals retire or move on. Developing more resilient models, such as embedding citizen science within government monitoring programs, establishing endowments for long-term community-based monitoring, or creating payment for ecosystem services schemes that recognize volunteer contributions, will be essential for ensuring that citizen science can fulfil its potential as a lasting component of river restoration practice rather than a series of ephemeral projects. In this context, the growing recognition of citizen science in environmental policy and the increasing emphasis on public participation in water framework directives and similar regulatory instruments offer opportunities for more stable and institutionalized support, provided that the citizen science community can continue to demonstrate the reliability, relevance, and added value of volunteer contributions to river science and restoration. Table 2 outlines the future challenges for each theme discussed above.

Table 2. Summary of future challenges for citizen science in river restoration projects.

	Future challenge	Key aspects
Data quality vs quantity	Trade-off between scale and accuracy	Standardized protocols, training, QA/QC systems, volunteer motivation, long-term datasets
Participation and inclusivity	Limited representativeness of volunteers	Inclusion strategies, removal of barriers, partnerships with local communities
Organisational capacity	Limited funding	Dependence on short-term grants, need for long-term funding models
	Lack of coordination	Data sharing, methodological alignment, cross-project learning
	Technical infrastructure gaps	Digital divide, access to tools and internet
Institutional integration	Limited uptake in policy and management	Trust-building, validation frameworks, co-design with decision-makers
Scalability	Maintaining quality and engagement at larger scales	Governance structures, training systems, adaptive coordination
Data growth and complexity	Managing large, heterogeneous datasets	Interoperability, data standards, advanced analytics
Technology integration	Balancing AI and human participation	Human–AI collaboration, maintaining engagement
Governance and sustainability	Fragile funding and project continuity	Institutional embedding, diversified funding, payment for ecosystem service (PES scheme)

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Links

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