TECHNICAL REPORT

Model Framework for a Citizen Science Water Monitoring System in the Limpopo River Basin

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Front cover photo: A shake of hands as citizen scientists receive citizen science water monitoring tools donated by GroundTruth (*photo*: GroundTruth).
Back cover photo: Citizen scientist trainees sit with a citizen science trainer and look over a mini stream assessment scoring system (miniSASS) sampling tray (*photo:* GroundTruth).

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Introduction

The Limpopo River basin is a critical source of resources for a large transboundary area, including regions of Botswana, Mozambique, South Africa, and Zimbabwe. However, it faces intensifying pressures from increasing competition for limited water and arable land, hydro-climatic extremes, rising temperatures, increased frequency of droughts and floods, land degradation, declining water quality, rapid urbanisation, and population growth (Zhu and Ringler 2012, Mwenge Kahinda et al. 2016, Botai et al. 2020, O'Brien et al. 2022, Ghosh et al. 2025). These stressors interact, threatening biodiversity, increasing food and water insecurity, and undermining community resilience to climate change, with women and children most vulnerable (UNICEF 2023, Wang et al. 2024). The pressures also act in a negative feedback loop, where land degradation and deteriorating aquatic ecosystems impair ecosystem services, further diminishing livelihoods and biodiversity (Sutton et al. 2016, Ekka et al. 2023). As is common across the globe, data gaps undermine any efforts to improve management.

To address pressing water-related challenges in the Limpopo River basin, the CGIAR International Water Management Institute (IWMI) and Limpopo Water Commission (LIMCOM), in conjunction with many key partners and collaborators, built a Digital Twin[1,2] of the basin to assist in the monitoring and management of water resources (Garcia Andarcia et al. 2024a, 2024b, Vickneswaran et al. 2024). The Digital Twin aims to provide near real-time data on various aspects of water resource management, integrating and artificial intelligence (AI) virtual assistant chatbot, and machine learning for efficient data interrogation by water managers and stakeholders. This represents a huge milestone for global transboundary water resources management and innovation in data collection and visualization.

To further the power and utility of the Digital Twin, IWMI are collaborating on a range of ongoing research and development to increase its data capturing and handling capacity. A core focus of this work is integrating citizen science data streams through the project, *Citizen Science for Water Management in Limpopo River Basin*[3]. A large body of research, development, design, and implementation regarding the integration of citizen science into the water resource monitoring and management in southern Africa, co-led by GroundTruth and IWMI, was completed within the CGIAR Initiative on Digital Innovation (Pattinson et al. 2022, 2023b, 2023c, 2023a, 2024a, 2024b, Koen et al. 2023, Graham et al. 2024a). The CGIAR Accelerator for Digital Transformation and Digital Innovations for Water Secure Africa (DIWASA) initiatives are now building on that platform for the *Citizen Science for Water Management in Limpopo River Basin* project. The inclusion of citizen science aims to enhance the role of communities in informing water management decisions by co-engaging citizens in data collection and water resources governance. Involving communities through citizen science creates pathways for civic action based on scientific data, democratizes data collection, and benefits all stakeholders in the basin through the host of positive outcomes that come from citizen science co-engagement. Overall, the goal is to co-create a system wherein operational citizen science is valued by decision-makers and drives meaningful change in water management.

The *Citizen Science for Water Management in Limpopo River Basin* project is modular, building towards the overall objective through an iterative workflow. The first step in the process required co-development a model framework for a citizen science water monitoring system for

[1] https://digitaltwins.demos-only.iwmi.org/
[2] https://www.cgiar.org/news-events/news/digital-twin-of-the-limpopo-basin-advances-with-new-prototype/
[3] https://www.iwmi.org/projects/data-driven-digital-social-innovations-in-africa/

the Limpopo River basin. This required collaborative conceptualisation, research, development, design, and implementation across a range of facets, including partner network establishment, capacity building for trainers and citizen scientists, technological innovation with citizen science tools, establishing incentivization structures, and operationalising interactive data handling, visualisation, and reporting. GroundTruth and IWMI co-lead the process, leveraging decades of experience in citizen science, drawing particularly on the highly successful Enviro-Champs initiative (Graham et al. 2004, 2024b, 2024a, Taylor et al. 2012, 2022, Taylor and Taylor 2016, O'Donoghue et al. 2018, Graham and Taylor 2018, Goldin et al. 2021, Lepheana et al. 2021, Lotz-Sisitka et al. 2022, Madikizela 2022, Pattinson et al. 2023c, 2023b, 2023a, 2024b, 2024a, Russell et al. 2024, Warner et al. 2024, WWQA 2024, Curtis et al. 2025). The model framework for the Limpopo River basin comprises, loosely, a 6-step process (Figure 1). The steps are not discrete, with various components requiring simultaneous input or adaptive iteration. While this model framework describes the process followed for the Limpopo River basin case, with project specific links to components such as the CGIAR LIMCOM Digital Twin, it is framed as a guideline that can be adjusted as needed for future project activities, or as a scaffold for scaling to other transboundary river basins in Africa or the world.

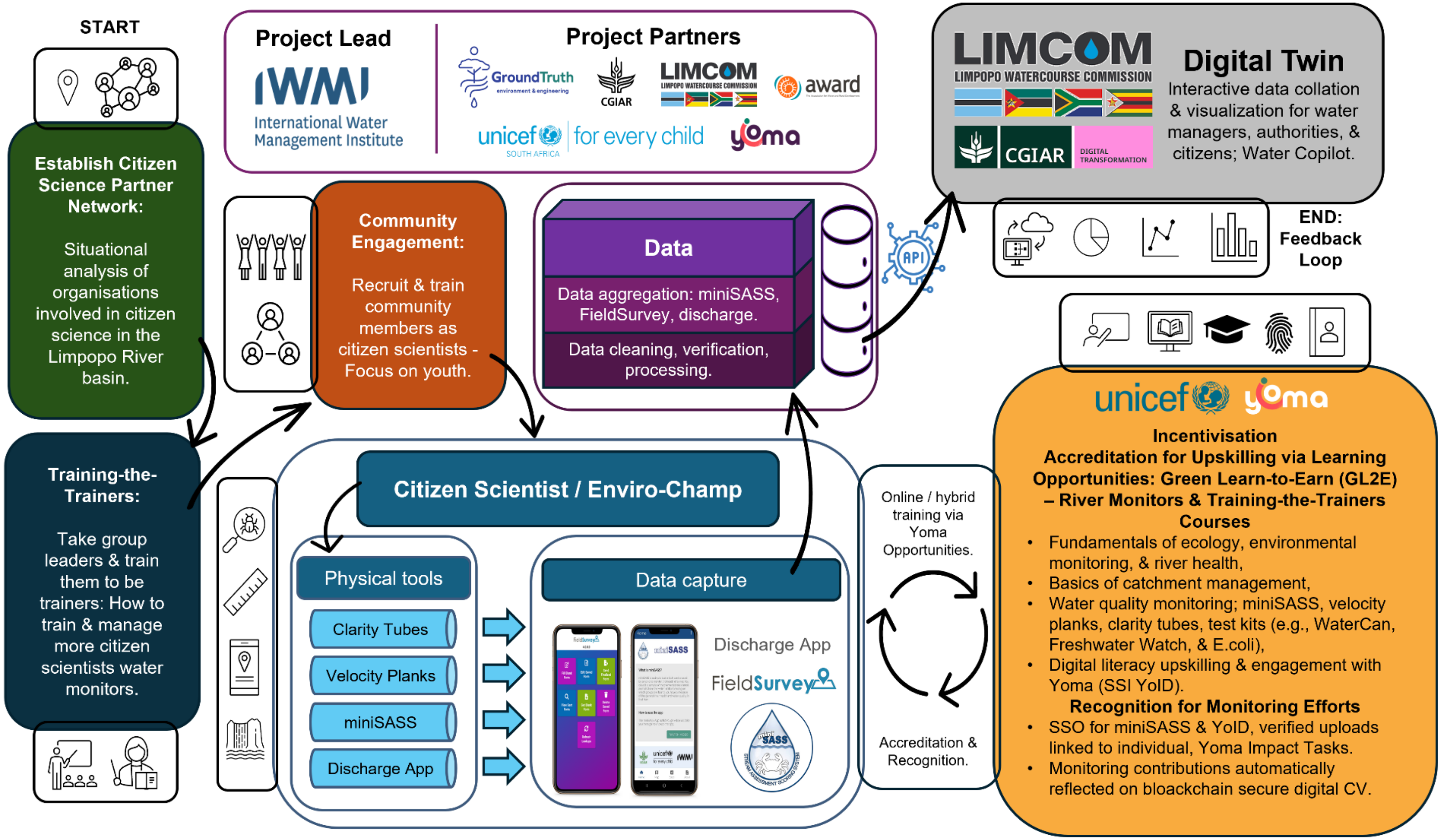

Figure 1. Overview of conceptual citizen science model framework for the Limpopo River basin. Various stages (non-discreet) are shown in a general recommended flow, including a situational analysis of the potential network of partners, Training-the-Trainers, community engagement, training, data collection, handling, and transfer to the CGIAR Limpopo Watercourse Commission (LIMCOM) Digital Twin, and citizen scientist incentivisation via the United Nations Children's Fund (UNICEF) Youth Agency Marketplace (Yoma). (*Source:* authors' creation)

Step 1: Establish Citizen Science Partner Network

A basin-wide citizen science monitoring system is best founded on a strong and diverse network of organisations and individuals who are willing and able to co-produce environmental data, interpret those data in context, and act on the insights. The process should begin with a structured situational analysis to identify active and prospective role players across government departments, non-government organisations, community-based organisations, academic and training institutions, and transboundary conservation entities. The analysis should map who is already engaged in citizen science or adjacent monitoring, what capacities and resources are available, and where strategic collaboration can strengthen coverage, legitimacy, and long-term sustainability (Lotz-Sisitka et al. 2022, Pattinson et al. 2023c, Mickelsson et al. 2024).

Early Engagement and Inclusivity

Experience from the Limpopo River basin indicates that proactive outreach, transparent communication, and inclusive design are critical[4,5,6] (Garcia Andarcia et al. 2024b). Partners should be approached with a clear articulation of objectives, anticipated benefits, and the roles they may play within the network. Inclusivity should be a guiding principle, with particular attention to organisations that serve vulnerable or under-represented communities. Engagement should seek to link disparate initiatives into a coherent community of practice so that knowledge, methods, and support circulate across the network rather than residing in isolated silos (Russell et al. 2024).

Define a Data-to-Action Use Case at the Outset

A key recommendation is to develop a use case that specifies the data-to-decision pathway before any large-scale data collection begins. This use case should state where citizen science data will go, who will recognise, validate, and use them, and how those data will inform adaptive management. Without such a pathway, citizen science risks operating as an isolated activity that does not reach managers or authorities. In practice, this means identifying end-users, agreeing minimum data standards and validation routines, and aligning with visualisation and reporting platforms recognised by decision-makers, for example a Digital Twin environment[7] (Garcia Andarcia et al. 2024a, Yang et al. 2024, Ghorbani Bam et al. 2025).

Information Gathering and Coordination

To support planning and transparency, it is advisable to circulate a comprehensive survey to prospective partners. The survey should capture:

- Organisational contact information;
- The number and distribution of active citizen scientists;
- Recruitment approaches and any inclusivity prerequisites;
- Training received by citizen scientists and the materials used for education or skills development, whether in-person courses, virtual workshops, or online short courses;
- The water bodies monitored;

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[4] https://www.iwmi.org/blogs/citizen-scientists-take-the-lead-in-tracking-southern-africas-transboundary-river-basin/
[5] https://www.iwmi.org/blogs/iwmi-introduces-cutting-edge-ai-citizen-science-tools-to-the-limpopo-river-basin/
[6] https://www.iwmi.org/blogs/a-network-of-citizen-scientists-to-protect-freshwater-resources-in-southern-africa/
[7] https://www.cgiar.org/news-events/news/digital-twin-of-the-limpopo-basin-advances-with-new-prototype/

- Tools and parameters collected, such as the mini stream assessment scoring system (miniSASS[8]), a citizen science biomonitoring tool enables communities to monitor river health by sampling aquatic macroinvertebrates (Graham et al. 2004, 2015, Graham 2012, Graham and Taylor 2018, Pattinson et al. 2022, 2023a, 2023b, 2024a, Taylor et al. 2022, Koen et al. 2023); clarity tubes, citizen science tools that measures water clarity, providing insights into water quality (Kilroy and Biggs 2002, Dahlgren et al. 2004, Graham et al. 2024a); velocity planks, citizen science tools that measure stream velocity and discharge (Wilm and Storey 1944, Fonstad et al. 2005, Pike et al. 2016, Graham and Taylor 2018, Despax et al. 2020); or other chemistry or habitat observations, such as via Freshwater Watch[9] monitoring (Scott and Frost 2017, Warner et al. 2024, Bishop et al. 2025);
- Data capture methods, whether pen and paper, Field Survey[10], the miniSASS app[11], or other platforms;
- Data storage approaches and whether data are curated in Excel spreadsheets, web databases, or institutional portals;
- Quality assurance and validation routines;
- Analysis and visualisation practices, such as charts, maps, dashboards;
- Feedback and communication channels with citizen scientists, including WhatsApp, chatbots, or SMS;
- How data are used and by whom, for instance internal management, engagement with local authorities, or policy recommendations; and
- Whether citizen scientists are incentivised and how, for example certified training, salaries, or stipends.

The survey should also assess logistical readiness for capacity-building, including whether partners can host Training-the-Trainers workshops (e.g., access to facilities, nearby rivers for demonstrations, and accommodation), whether co-funding is available to meet travel or subsistence costs, and whether suitable people can be nominated to become trainers and coordinators.

Before administering surveys or collecting personal information, appropriate ethics approval must be obtained. Data privacy protocols and informed consent also need to be embedded across systems. A recommendation for replication is to include a short ethics and data privacy statement, as well as consent for terms of use, in all onboarding materials, with clear contact points for queries and withdrawal.

Network Reach and Partner Interest

The Limpopo River basin is a good example of the need to set realistic expectations for coverage while aiming for a broad, transboundary footprint. In the case of the Limpopo River basin, which spans Botswana, Mozambique, South Africa, and Zimbabwe, initial engagement through the situational analysis reached twenty-six organisations conducting, or interested in initiating, citizen science water resources monitoring. These included the United Nations Educational, Scientific and Cultural Organization (UNESCO) Vhembe, Kruger-to-Canyons (K2C), Groot Marico, and Waterberg Biosphere Reserves, the Diamonds on the Sole of their Feet Initiative, South African National Parks (SANParks) Kruger National Park, IIE-MSA,

[8] https://minisass.org/
[9] https://www.freshwaterwatch.org/
[10] https://fieldsurvey.co.za/
[11] https://play.google.com/store/apps/details?id=com.rk.amii

Botswana Water Partnership through the Global Water Partnership Southern Africa (GWPSA) and LIMCOM, Instituto Superior Politécnico de Gaza (ISPG), Gonarezhou Conservation Trust, and the Dabane Trust. A similar programme elsewhere should also aim to engage a mix of conservation actors, education and training institutions, government and non-government organisations, and civil society groups, and should plan for staggered onboarding as ethics approval, logistics, and co-funding are confirmed. Once ethics approval is in place, surveys can be distributed, allowing ample time for responses and follow-up. These responses should provide sufficient detail to plan the following steps.

Planning Capacity Building

Following the situational analysis and stakeholder commitments, it is recommended that Step 1 includes co-development of a practical schedule for Training-the-Trainers workshops. This schedule needs to balance geographic reach, partner readiness, and budget constraints. A draft schedule may range over days, weeks, or months. Proposed host sites need to be at accessible locations that provide suitable facilities (e.g., a board room with electricity, enough seating, internet access, and means to project presentations) and nearby rivers for field demonstrations. Where a hosting location cannot be secured, the schedule should remain flexible to accommodate late-stage co-funding or to move training online until in-person options become viable.

Resource Mobilisation and Constraints

Address financing realities openly during Step 1. If the available budget cannot cover partner travel, accommodation, and materials, then co-funding arrangements should be explored early. Many citizen science organisations face structural funding constraints, particularly where larger programmes have ceased or where priorities have shifted. Planning for cost-sharing, micro-grants, or sponsorships, and documenting these arrangements in memoranda of understanding, reduces uncertainty and sets realistic expectations for participation.

Other recurrent risks in Step 1 are low response rates and uneven transboundary representation. Potential mitigation strategies include multiple rounds of outreach through trusted intermediaries, short and clear information packs and surveys translated into relevant languages, and flexible training options. Another risk is over-promising integration without defined use cases. Ensure that uses cases are co-developed (see above) to ensure that participation meets partner priorities.

Recommended Outputs of Step 1

At the end of Step 1, some recommended outputs include:

1. A documented situational analysis;
2. A confirmed list of partners with focal points and contact details;
3. Ethics clearance from relevant authorities and data privacy provisions;
4. Completed surveys summarised in a coordination log;
5. A preliminary Training-the-Trainers schedule with proposed venues and dates;
6. Explicit use cases that tie citizen science data collection to situationally relevant, co-designed priorities; and
7. A resource mobilisation tracking system that records co-funding commitments and outstanding needs.

Step 2: Training-the-Trainers

Building a self-scaling, sustainable transboundary citizen science network requires local facilitators who can train, mentor, and manage teams of citizen scientists, as well as coordinate data, ethics, and communicate. A 'Training-the-Trainers' programme is recommended as the vehicle for onboarding and community-level mobilisation. The objective is not merely to teach use of citizen science water monitoring tools; it is to cultivate trainers who understand catchment context, environmental citizen science pedagogy, digital data capture workflows, and data-to-action pathways, and who can support others to engage meaningfully over the long-term.

Workshop Design Principles

The workshop should be designed for group leaders rather than general citizen scientists. The recommended curriculum integrates three strands, each with practical outcomes:

- Basics of catchment processes and aquatic ecology: Building an environmental understanding is important for trainers to situate monitoring and capacity building within their local hydrological and socio-ecological context. It also places trainers in a position to interpret what their data mean and how monitoring and engagement might drive management actions.
- Citizen science tools and methods: A core component needs to be building the practical and theoretical skills behind using citizen science instruments and related digital systems accurately and safely. This must be followed by how to teach those skills to others, including constructive feedback and safety in the field.
- Digital workflows: Knowledge and skills need to be built concerning the digital ecosystem surrounding technologically integrated citizen science monitoring and reporting. Training need to cover all aspects of the data and digital workflow, from data capture to curation, validation, visualisation, reporting, and feedback, including the role of data capture platforms and the route into decision support environments such as a CGIAR LIMCOM Digital Twin.

In the Limpopo River basin experience, the Action Learning 5-Ts framework (i.e., Tune-in, Touch, Talk, Think, and Take Action) provided an essential pedagogical scaffold for the Training-the-Trainers Workshops (O'Donoghue et al. 2018). Trainers learned to facilitate engagement, develop and compliment local knowledge, and support themselves and others to plan and implement change projects that connect locally relevant problems with data and action.

To widen participation, materials should be progressively translated into relevant languages and adapted for clarity and accessibility where possible. Digital barriers should be anticipated and mitigate where possible. For example, workshop design can build in offline data capture and presentation options, low-mobile-data training assets, and clear guidance on safe field practices. Facilitators need to remain alert to where participants may have differing literacy or technology familiarity and account for that adaptively within training implementation.

Training should embed quality assurance and ethics from the start. Facilitators must ensure that trainers understand informed consent, data privacy principles and practicalities, compliance with local regulations, and data quality and validation standards. Moreover, they must be able to communicate these to citizen scientists they subsequently train or mentor. Ideally, programmes should provide simple ethics and data protection statements for to guide training and further engagement.

Core Content and Pedagogy

A comprehensive Training-the-Trainers workshop should cover:

- Fundamentals of catchment processes and aquatic ecology;
- Citizen science tools and their correct use, including miniSASS surveys for aquatic macroinvertebrates, clarity tube measurements for water clarity, and velocity plank observations for discharge;
- Digital data capture via the miniSASS app (which can record miniSASS survey data, as well as other water quality monitoring measurements such as clarity tube water clarity readings, water temperature, electrical conductivity (EC), dissolved oxygen (DO), pH, and observational notes, with all associated metadata and photos) or Field Survey app (customisable for bespoke form-based data capture), including detailed walkthroughs of offline functionality, geolocation, timestamps, and photo evidence;
- Data handling basics, including standard operating procedures for cleaning, verification, and storage;
- Contextualising data for management decisions, including how monitoring flags hotspots and trends;
- Engagement with online environments, including the United Nations Children's Fund (UNICEF) Youth Agency Marketplace (Yoma) platform[12] for accreditation, impact recognition, and learner support, as well as the CGIAR LIMCOM Digital Twin for data interaction and visualisation;
- Practical sessions that include supervised field demonstrations, short teaching experiences where trainees present tool use to peers and engage in peer-to-peer learning, and constructive feedback that builds confidence without undermining enthusiasm.

Candidate Selection and Prerequisites

Experience from the Limpopo River basin and other citizen science mobilisation initiatives (Taylor and Taylor 2016, Lepheana et al. 2021, Pattinson et al. 2023c, 2024b) shows that selection of people to go through the Training-the-Trainers workshops benefits from clear prerequisites that balance competence and inclusivity. Recommended prerequisites include completion of an entry-level water monitors course, such as the *Green Learn-to-Earn (GL2E) – River Monitors Course*[13] (developed by GroundTruth in partnership with Rhodes University's Environmental Learning and Research Centre (ELRC) and the Duzi-uMngeni Conservation Trust (DUCT), and hosted on the Atlas Learning Management System (LMS)[14]), the ability to travel to and attend the full workshop, access to a smartphone for field and data capture, and functional English proficiency (though this requisite can be overcome by working with strong teams that support each other with translation and peer-to-peer learning) (Pattinson et al. 2023c, Russell et al. 2024). Programmes should explicitly welcome women and youth and should provide alternative formats or translation where possible to broaden participation. Trainers should be nominated by partner organisations and should demonstrate an environmentally conscious spirit with interest in facilitation, community engagement, and driving positive impact, rather than purely technical skills alone.

[12] https://yoma.world/
[13] https://yoma.world/opportunities/019946d2-575f-7f89-a600-47b4fd1f8d3a
[14] https://atlas.org.za/river-water-monitoring/

Coordination, Logistics, and Procedure

Setting up a transboundary network of citizen science stakeholders and coordinating ambitious multi-national Training-the-Trainers workshops requires significant effort from multiple parties. Coordination must be clear and inclusive. It is recommended to identify central locations for the workshops that maximise partner participation, to circulate dates well in advance, and to provide detailed pre-workshop communication covering transport, accommodation, required materials, and preparatory tasks. Where budgets are constrained, programmes should plan for co-funding by hosting partners and participants, and should document cost-sharing arrangements to avoid last-minute withdrawals. Flexibility in scheduling is essential in transboundary contexts where travel and accommodation can be unpredictable.

Equally important is coordination with relevant local and national authorities to ensure that proper procedures are followed and the required permissions, visibility, and political support are secured. Ideally, workshops should be formally endorsed by basin governance structures and, where appropriate, attended by designated representatives. For example, in the Limpopo River basin, all Training-the-Trainers workshops required approval from LIMCOM as well as attendance by a Member State representative from the host country. Logistic planning also needed to allocate time for local leaders and the LIMCOM representative to deliver opening remarks. Ensuring this co-engagement with governance structures reinforces legitimacy and fosters stakeholder ownership.

Implementation

Delivery should be co-facilitated with the host organisation to strengthen ownership and ensure local relevance. All implementation requirements and arrangements should be checked and ready prior to workshop kick-off. For example, venues should be verified for suitability in terms of safe access to a nearby stream or river for field work, reliable power, and safe storage of equipment. Each workshop day should blend theory, practice, and reflection. For example, an opening day can situate trainees and their Change Projects within the basin context, a second day can focus on tools and supervised practice, and a final day can emphasise digital capture, data sharing, reporting, and the facilitation skills needed to guide others through online learning and verification (Lotz-Sisitka et al. 2022, Mickelsson et al. 2024, Russell et al. 2024).

Assessment, Accreditation, and Recognition

Recommended assessment includes short teaching practicums and facilitator review of tool use and digital data capture competencies. As an incentive and acknowledgement of participation, trainers should receive formal recognition on successful workshop completion. For instance, a certificate of completion can be given in person to attendees at the conclusion of the workshop. Alternatively, if the workshop infrastructure is sufficiently advanced, recognition could be linked to a digital platform such as becoming a ‘learning opportunity’ on Yoma. In this case, completion of the workshop could be captured within a person’s unique, blockchain secured digital self-sovereign identity (SSI), termed the Yoma Identity (YoID), forming a verified micro-credential within their digital curriculum vitae (CV). Where feasible, further activities or achievements, such as further training and mentoring activities, can go towards further building a secure digital record of contributions and competencies. This recognition creates incentives for sustained engagement and potentially supports employability pathways in the Green Economy.

Recommended Outputs of Step 2

Potential outputs for Step 2 include:

1. A practical facilitation plan for training citizen scientists at partner sites;

2. A set of locally adapted materials for training and practice of tool use and digital capture;
3. A cohort of trained facilitators with documented competencies (potentially in the form of verified digital identities);
4. An assessment and accreditation record for trainers; and
5. A post-workshop support plan that includes communication channels and options for potential refresher courses.

Step 3: Community Engagement

Community engagement to onboard community members as citizen scientists is the next critical step that launches the partner network and trained facilitators into an operational, place-based citizen science water resources monitoring system. It is recommended that organisations recruit, train, and mentor citizen scientists in ways that nurture environmental literacy, strengthen social fabric, and generate validated, management-ready data.

Building a Local Network of Citizen Scientists

Recommended practice is to recruit through local partner organisations and community networks, with explicit attention to youth and women to support inclusion and green livelihood pathways. Recruitment should communicate roles, safety requirements, time commitments, and how participation links to potential livelihood improvement. A short application plus an interview helps identify motivated candidates and ensures physical capacity for fieldwork where needed. Inclusive, co-engaged processes are important for legitimacy and sustained participation (Taylor and Taylor 2016, Vallabh et al. 2016, Dörler et al. 2021, Lotz-Sisitka et al. 2022, Pattinson et al. 2023c, Mickelsson et al. 2024).

The safety of participants and transparency with data usage should be considered during recruitment and onboarding. This can be done through incorporating informed consent procedures, privacy notices, and data handling that is compliant with relevant standards, such as the Protection of Personal Information Act (POPIA)[15] and General Data Protection Regulation (GDPR)[16]. Where ethics statements are developed, they should be plain-language, translated where needed, and include opt-out and feedback details. This safeguards participants and builds trust, prerequisites for mutually beneficial participation (Bowser et al. 2017, Pierce and Evram 2022, Purtova and Pierce 2024).

Training Citizen Scientists: Content, Pedagogy, and Practice

Similar to the background covered for the Training-the-Trainers workshops, onboarding and training of citizen science monitors should combine catchment and aquatic ecology fundamentals with hands-on use of accessible tools and digital capture workflows. An Action Learning approach can once again prove useful, involving a mixed approach of lectures, practical field demonstrations, peer-teaching practicums, and reflective sessions that connect data to action. Training should focus attention on processes related to accurate, precise, and standardised data collection practices to build trust in the citizen science process and increase the possibility of the data entering data-to-action pathways (which is heavily reliant on trust in the data) (Freitag et al. 2016, Aceves-Bueno et al. 2017, Krabbenhoft and Kashian 2020, Balázs et al. 2021, Hegarty et al. 2021, Skarlatidou et al. 2024). This co-engaged, mixed, peer-to-peer social learning builds environmental literacy, agency, and stewardship. Safety during training and post-training is paramount: Training should include field safety protocols, risk assessment and mitigation, and escalation routes for reporting or dealing with potential

[15] https://www.gov.za/sites/default/files/gcis_document/201409/3706726-11act4of2013protectionofpersonalinforcorrect.pdf
[16] https://gdpr-info.eu/

hazards. It is also important to consider and maximise inclusivity. For example, key materials and user interfaces can be translated into local languages where possible, while audio-visual guides or tutorial videos can reduce engagement and understanding barriers, especially for first-time participants or those with limited formal education exposure. Remote and blended learning should be supported with low-bandwidth content, printable support materials, and text-chat-based help (Lotz-Sisitka et al. 2022, Mickelsson et al. 2024, Russell et al. 2024).

Recommended Outputs of Step 3

By completion of community engagement, programmes should have:

1. Quick-reference guides, onboarding materials, and relevant training and education materials for all background, methods, and tools used in recruiting, training, and deploying citizen science water monitors;
2. A documented roster of citizen scientists with consent records, contact details, training completion logs, and verified competency records, preferably with secure digital identity profiles; and
3. A communication plan and feedback schedule linking citizen-science outputs to management actions, including incident escalation routes and summary dashboards, to sustain motivation and show impact.

Step 4: Data Collection, Curation, and Storage

This step aims to translate the collective efforts of a trained network of citizen science water resource monitors into reliable, management-ready datasets. Programmes should start by designing data capture workflows that are simple, inclusive, and robust. Proportionate validation and curation should be embedded so that data are Findable, Accessible, Interoperable, and Reusable (FAIR) (Wilkinson et al. 2016) and recognised within decision-support environments. Water-quality datasets can complement statutory monitoring, fill spatial and temporal gaps, and support national reporting on the Sustainable Development Goals (SDGs), including SDG 6.3.2 on ambient water quality and SDG 6a-b, when the programmes that generate those datasets are co-designed for data quality, inclusion, and action by decision-makers (Fritz et al. 2019, Bishop et al. 2020, Fraisl et al. 2020, 2023, Suman and Schade 2021, Mukuyu et al. 2023, Warner et al. 2024).

Design Principles for Data Capture

Recommended practice is to use standardised forms and checklists, mobile apps with offline capability, and embedded prompts for geolocation, timestamps, and photographic evidence. A comprehensive and standardised data collection approach will improve completeness and reliability. Platforms such as miniSASS and Freshwater Watch demonstrate these features in practice and can be adapted for basin contexts (Taylor et al. 2022, Pattinson et al. 2023a, Bishop et al. 2025). Importantly, data collection needs to be co-designed to be culturally and situationally appropriate. Programmes should select water quality or ecosystem condition monitoring parameters and tools that are compatible with citizen science and relevant to local communities and authorities. Co-designing citizen science data collection to pair with conventional monitoring sites and parameters can allow cross-validation and trust building in both government reporting and the utility of citizen-generated data. This design thinking needs to be done early, given that all of the methods, tools, approaches, and background regarding data collection will need to be co-designed for local relevance with situated stakeholders and covered within the Training-the-Trainers workshops and citizen science onboarding in Steps 2 and 3.

Data Cleaning, Curation, and Transfer

Programmes should schedule periodic cleaning runs to resolve duplicates, remove incomplete training records, and correct obvious errors. Metadata should be enriched to record provenance, devices, validators, and transformations, supporting traceability and reuse; FAIR data guidance offer practical templates for documentation and curation[17] (Wilkinson et al. 2016). Generally, it is recommended to use repositories that implement persistent identifiers, licence declarations, and standard protocols for retrieval, then register metadata to enable discovery. Where photos are used for verification and communication, they should be housed in secure object storage and linked to observations via persistent identifiers.

Open licences should be adopted where possible for non-personal observation data, while private fields for personal information can be retained in an encrypted state for necessary use. Ideally, data and metadata should be published or accessible in both human- and machine-readable formats to facilitate reuse and interoperability. Institutional portals such as the UNESCO Intergovernmental Hydrological Programme's Water Information Network System (IHP-WINS)[18] and community platforms such as miniSASS or Freshwater Watch demonstrate workable publication and interoperability models.

Data models and application programming interfaces (APIs) should be designed so that curated datasets can flow, with controlled latency, into visualisation and decision-support platforms such as a Digital Twin. For example, the miniSASS environment provides authentication, observation, and image APIs, with published OpenAPI documentation and authentication flows[19,20,21,22,23,24].

Responsible Data Practices

Once again, it is critical that data ecosystems have data privacy, security, and ethics built in by design. All data capture tools should prompt for consent, display privacy notices, and implement role-based access to personal data. Data curation, storage, transfer, and visualisation should adhere to strong security and privacy protocols, especially where third parties are required within the data ecosystem. Data validation routines can include supervisor-observed first submissions, field photos for species verification, automated flagging of improbable values, and randomised audits for large datasets.

Recommended Outputs of Step 4

The recommended outputs of Step 4 include:

- Operational standard operating procedures for field data capture, including use and operation of physical tools such as clarity tubes, velocity planks, and water test kits, as well as digital tools such as the miniSASS app.
- A centralised, secure repository implementing FAIR principles, persistent identifiers, open licences for non-personal data, and clear provenance records.
- Documented protocols for data curation and quality assurance routines, including scheduled cleaning, automated flags, random audits, and supervisor validations.

[17] https://ukdataservice.ac.uk/learning-hub/research-data-management/plan-to-share/fair-data-principles/
[18] https://cs.ihp-wins.unesco.org/DataViewer
[19] https://kartoza.github.io/miniSASS/developer/profile/
[20] https://kartoza.github.io/miniSASS/developer/3rd-party-api-access/
[21] https://kartoza.github.io/miniSASS/developer/sites/
[22] https://kartoza.github.io/miniSASS/developer/observations/
[23] https://minisass.org/redoc/
[24] https://ketankartoza.github.io/miniSASS/developer/authentication/

- API integration plans and tested endpoints to transfer curated datasets to visualisation and decision-support platforms.

Step 5: Data Visualisation and Reporting via Integration with a River Basin Digital Twin

Once citizen science data have been collected and curated, the next critical step is to transform these raw observations into actionable insights. This requires summarising and visualising the data in formats that are accessible, interpretable, and relevant to decision-makers and communities alike. Effective reporting should provide dynamic dashboards, spatial layers, and trend analyses that enable managers to identify hotspots, track changes over time, and prioritise interventions. Establishing formal, rapid channels for reporting pollution events, especially with accompanying evidence such as geo-tagged photos with short narratives, and linking these to authorities, can support targeted management actions (Quinlivan et al. 2020a, Hegarty et al. 2021, Graham et al. 2024a, Pattinson et al. 2024b). Equally, data visualisations and insights must feedback to citizen scientists, ensuring transparency and reinforcing the value of their contributions. This can help ensure that their contributions are not only transparently linked to visible outcomes, but that the collectors are directly and openly valued. Through this co-learning, recognition, communication, and visible impact tracking, participant retention and motivation can be improved, driving the sustainability of the model (Alender 2016, West et al. 2021, Delfine et al. 2024).

Modern decision-support platforms offer powerful opportunities to achieve this, and one of the most promising approaches is integration with a river basin Digital Twin, a virtual representation of the basin that can host real-time data streams, predictive models, and interactive tools for governance and adaptive management (Botai et al. 2023, Yang et al. 2024, Ghorbani Bam et al. 2025, Pal et al. 2025). Integration with a Digital Twin is an ideal, but completely optional approach that compliments whatever structures are set in place to summarise, visualise, and / or use citizen science water monitoring data.

In the case of the Limpopo River basin, IWMI and LIMCOM, in conjunction with key partners and collaborators, have developed a Digital Twin[25,26,27,28,29,30,31] of the basin to assist in the monitoring and management of water resources (Afham et al. 2024, Garcia Andarcia et al. 2024a, 2024b, Vickneswaran et al. 2024). Recent developments have aimed to start integrating citizen science data feeds into the CGIAR LIMCOM Digital Twin. Data in the Digital Twin can then be queried using natural language through the built-in Water Copilot[32,33,34,35] (Vickneswaran et al. 2024), a virtual AI-powered assistant. Through this system, the CGIAR LIMCOM Digital Twin has been shaped into a tool that can turn curated citizen-science datasets into actionable information with intelligent, user driven interaction and feedback. Managers, authorities, and communities can interrogate near real-time, citizen generated evidence and plan responses or track changes accordingly at transboundary scale.

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25 https://digitaltwins.iwmi.org/programmes/limpopo-river-basin/
26 https://www.iwmi.org/multimedia/water-managers-get-hands-on-with-the-ai-powered-digital-twin-for-the-limpopo-river-basin/
27 https://limpopocommission.org/article/digital-twin-of-the-limpopo-basin-advances-with-new-prototype/
28 https://digitalearthafrica.org/en_za/ai-and-satellite-imagery-better-estimate-water-levels-in-dams/
29 https://limpopocommission.org/article/africas-first-prototype-digital-twin-comes-home-to-the-limpopo-river-basin/
30 https://digitaltwins.iwmi.org/2025/10/ai-driven-digital-twin-for-water-management-for-limpopo-river-basin-and-inclusive-integration-with-citizen-science/
31 https://www.iwmi.org/news/transboundary-collaboration-on-the-limpopo/
32 https://www.iwmi.org/projects/water-copilot/
33 https://www.iwmi.org/multimedia/water-managers-get-hands-on-with-the-ai-powered-digital-twin-for-the-limpopo-river-basin/
34 https://digitaltwins.iwmi.org/2025/09/ai-agent-by-iwmi-and-microsoft-to-drive-new-thinking-in-water-management/
35 https://digitaltwins.iwmi.org/2025/09/iwmi-and-microsoft-use-ai-to-tackle-southern-africas-water-challenges/

Digital Twin Integration Architecture and Data Pathways

Building a Digital Twin of a river basin, especially at a large, transboundary scale, requires substantial planning, design, construction, funding, and multidimensional collaboration across diverse skillsets (Botai et al. 2023, Yang et al. 2024, Ghorbani Bam et al. 2025, Pal et al. 2025). Assuming a Digital Twin platform already exists, or that all other required development pipelines are being operationalised, citizen science data can be integrated through a simple and pragmatic construction and implementation pathway:

- Set up a citizen science data capture environment, including physical data collection tools and digital recording structures.
- Curate data with metadata that are human- and machine-readable, standardised, and stored in interoperable formats within secure repositories, adhering to FAIR data principles.
- Transform data pipelines as needed to the Digital Twin's canonical schema and transfer via authenticated APIs.
- Visualise and summarise data within the Digital Twin, potentially exposing the data to an AI assistant where possible for intelligent interaction.

Notably, the United Nations Environment Programme (UNEP) custodian guidance encourages countries to report on water quality for SDG 6.3.2 at Level 1 using core parameter groups and at Level 2 through various other parameters, including biomonitoring approaches (UN Water 2016, UNEP and UN Water 2018, UNEP 2021, 2023, 2024). Therefore, integrating citizen-science water quality monitoring through techniques such as Freshwater Watch and miniSASS form Level 1 and 2 parameter monitoring can potentially form an SDG-aligned layer within a Digital Twin to support national SDG reporting (Bishop et al. 2020, Taylor et al. 2022, Warner et al. 2024).

Recommended Outputs of Step 5

Should the citizen science model include integration with a Digital Twin, suggested outcomes of Step 5 include:

- A documented plan for citizen science data collection, with an API ingestion plan. This should include OpenAPI specs, FAIR data policies, and mapping architecture for citizen science data feeds into the Digital Twin schema.
- Co-designed and operational visual layers and dashboards for citizen-science data in the Digital Twin portal, including time series and spatial data visualisations and photos.
- Tested, user-driven AI-assistant interaction and feedback mechanisms that can summarise citizen-science evidence and generate manager briefs in easy-to-understand, actionable formats.
- A feedback and adaptive management framework to notify stakeholders of data status and use or requests and actions taken, collectively ensuring that the Digital Twin serves a designed, multistakeholder-beneficial use case.

Step 6: Incentivisation

Incentivisation for citizen science sustains and motivate participation, improves data continuity and quality, and helps translate engagement into recognised skills and livelihood pathways (Alender 2016, Suman and Schade 2021, Moshi et al. 2023, Delfine et al. 2024, Koedel et al. 2024). Incentivisation for citizen science can take many forms, reflecting the diverse motivations that drive participation. These include intrinsic factors such as curiosity, learning, enjoyment, and a sense of contributing to science or environmental stewardship, social motivations such as community belonging and activism, and extrinsic incentives such as recognition, certified credentials, career development opportunities, and tangible rewards like stipends or vouchers (Fritz et al. 2019, Pateman et al. 2021, West et al. 2021). However, motivations and incentive structures can differ markedly between the Global North and Global South. In high-income contexts, intrinsic and altruistic drivers, such as contributing to science or conservation, often dominate, while in resource-constrained settings, practical incentives that offset participation costs (e.g., transport, mobile data), direct monetary payments, and pathways to skills recognition or employment can be critical for initial and sustained engagement (Paul et al. 2018, Capdevila et al. 2020, Quinlivan et al. 2020b, Walker et al. 2020, Fraisl et al. 2020, Lepheana et al. 2021, Weingart and Meyer 2021, Delfine et al. 2024). For youth especially, certified credentials, impact-linked rewards, and financial gain, when designed responsibly, can be powerful motivators, especially in the context of building verifiable records for employment in the green economy and water sectors (Lakomý et al. 2020, Constant and Hughes 2023). In the context of the Limpopo River basin, Yoma is being leveraged as a potent digital accelerator for motivating youth involvement in citizen science and the water commons[36]. Through UNICEF's Generation Unlimited, Yoma has operationalised such pathways with verifiable digital CVs, YoIDs, and tokenised rewards that convert into practical benefits[37].

Incentive Design Principles

Incentives can be primarily anchored in formal recognition of skills and verified contributions, which translate to unified value across borders – a vital characteristic in transboundary contexts. Thereafter, practical rewards to offset participation costs can be built in where possible and appropriate, motivating targeted or sustained contributions. Feedback is a key universal incentive; participants should see how their data inform management actions (e.g., via visualisation in a Digital Twin or within SDG reporting). Seeing data used can significantly strengthen the feeling of being valued and foster genuine stewardship over local environmental conditions (Lotz-Sisitka et al. 2022, Graham et al. 2024b). As in the case throughout development and implementation in all steps, incentive structures must respect consent and data protection. Digital identities and credential wallets should implement SSI principles, selective disclosure, and clear privacy notices to comply with relevant data regulations.

Sustainable Financing for Incentives

Generally, a robust incentive structure, especially one that provides direct payment to participants, requires a long-term financing model that recognises the economic value of healthy ecosystems and the communities that steward them. Ideally, onboarding communities as custodians of river systems and catchments should be framed as a service with measurable returns (Díaz et al. 2018, Vasiliades et al. 2021). Healthy ecosystems underpin agriculture, fisheries, tourism, and climate resilience, all of which have tangible economic implications (Palomo et al. 2021, Fuchs and Noebel 2022). Financial mechanisms could include watershed protection funds, biodiversity credits, and carbon offset markets, complemented by public–private partnerships and donor-backed sustainability funds (Jepson et al. 2023, Task Force on Nature Markets 2023). These instruments can channel resources into citizen science networks, training programmes, and monitoring activities, creating a feedback loop where local stewardship generates both ecological and financial dividends. Alternatively, models such as payment for ecosystem services offers a possible approach, where beneficiaries of ecosystem functions, such as water purification, carbon sequestration, and biodiversity conservation, contribute financially to those maintaining these services (Turpie et al. 2008, Osewe et al. 2023, Le et al. 2024). By quantifying and monetising these benefits, payment for ecosystem

[36] https://www.iwmi.org/blogs/a-network-of-citizen-scientists-to-protect-freshwater-resources-in-southern-africa/
[37] https://www.generationunlimited.org/yoma

services models create a direct link between ecological health and socio-economic value, ensuring that conservation is not seen as a cost but as an investment.

A 3-tier Incentive Framework in the Limpopo River Basin Model

Within the Limpopo River basin model, a three-tier incentive framework was co-designed to strengthen participation and sustain engagement. This framework operates principally within the Yoma digital incentive ecosystem, combining recognition-based micro-credentials with practical rewards to offset participation costs. The approach reflects recommended practice for citizen science incentivisation, balancing intrinsic motivations with structured extrinsic incentives that build verifiable records of achievement and create pathways to employment.

Tier 1: Micro-credential Recognition Pathway

The first tier focuses on formal recognition of skills and contributions. At its core is the YoID, the SSI wallet that binds verified learning and impact records to a portable digital CV. Youth completing online learning units (e.g., the *GL2E – River Monitors* or *Agroecology*[38,39] Courses) and validated field tasks receive credentials that can be shared securely with employers and programme partners. The Yoma platform documents these credentials and maintains a growing partner network, with active deployments across multiple countries. Course-linked micro-credentials are the key component of this pathway. Achievements issued as verifiable credentials through Yoma aim to improve employability and strengthen green skilling pathways. Beyond learning opportunities, impact credentials recognise verified contributions in the field through 'Impact Tasks'. These are recorded as impact badges within the digital CV, reinforcing the value of citizen science as a recognised contribution to environmental stewardship.

Tier 2: Financial Rewards Pathway

While non-financial incentives remain central, pragmatic financial mechanisms such as stipends can help offset costs like transport or mobile data in high-unemployment contexts, provided they align with long-term capacity building (Weingart and Meyer 2021). The second tier addresses practical financial barriers to participation through tangible rewards. In South Africa, and select other countries, verified activities can be linked to digital 'Zlto' tokens, blockchain-based tokens which are redeemable across a national vendor network for essentials such as airtime, mobile data, groceries, electricity, and transport[40]. These rewards help offset costs that might otherwise limit engagement, particularly for youth in resource-constrained settings. However, transboundary implementation presents challenges. ZLTO and similar redemption networks are not uniformly available across Africa. Consequently, the default incentive across the basin should remain recognition via credentials, with financial or voucher-based rewards introduced only where local partners can guarantee fulfilment. Where feasible, programmes should collaborate with country partners to build localised reward catalogues that reflect local needs and access, drawing on Yoma's marketplace patterns and documentation[41].

Tier 3: Engagement and Co-Creation Pathway

Beyond formal incentives secured via the Yoma platform, the third tier of the incentive design emphasises intrinsic motivators essential for sustained citizen engagement (Levontin et al. 2022). This tier cultivates agency and empowerment within communities by positioning

[38] https://atlas.org.za/agroecology/
[39] https://yoma.world/opportunities/0199a673-fcc4-7594-b103-87304d931393
[40] https://zlto.co
[41] https://yoma.world

participants as active contributors to the scientific process and knowledge co-creation (Tengö et al. 2017, 2021, Fernández-Llamazares et al. 2021, Zurba and Papadopoulos 2023). Their involvement fosters a sense of purpose and scientific literacy while integrating diverse perspectives, including indigenous and local knowledge systems, to ensure strategies resonate with community priorities (Bonney et al. 2009, Alender 2016, Phillips et al. 2019, West et al. 2021, Koedel et al. 2024, von Gönner et al. 2024b). Providing immediate access to actionable data, such as pollution hotspot identification, strengthens the perception that monitoring efforts lead to tangible management decisions (von Gönner et al. 2024a, Warner et al. 2024). This participatory approach builds trust between communities and authorities, reinforcing the legitimacy of citizen science as a driver of systemic impact (Eleta et al. 2019, Skarlatidou et al. 2024).

The incentive structure of this tier is relational rather than transactional: Participants gain influence over local water governance, visibility in basin-level dialogues, and opportunities to shape interventions that affect their livelihoods (Allf et al. 2022). Agency-driven incentives are not merely psychological, they can translate into tangible social capital and help foster leadership and community resilience (Taylor and Taylor 2016, Pattinson et al. 2023c). Mechanisms include participatory workshops, community-led monitoring plans, and transparent reporting of how citizen science data inform policy. Digital visualisation within the CGIAR LIMCOM Digital Twin and AI-driven feedback via the Water Copilot further enhance the sense of contribution to improved ecosystem health and community well-being. Ultimately, this tier complements recognition and financial rewards by embedding citizen science within inclusive governance structures, creating a durable foundation for sustained engagement.

Recommended Outputs of Step 6

A robust incentivisation programme design should have:

1. An incentives policy that specifies recognised tasks, consent and privacy provisions, quality assurance and verification prerequisites, cross-border reward rules, and principles for participatory engagement and feedback loops to ensure inclusion and trust-building.
2. A credentials and rewards playbook, potentially integrating a system such as Yoma's YoID and digital CV issuance with partner-backed vouchers or tokens where available, as well as guidance on structuring stipends or cost-offset mechanisms in contexts of high unemployment without undermining long-term capacity building.
3. A partner catalogue of green-economy career pathways linked to citizen science upskilling and contributions, complemented by opportunities for participants to engage in governance dialogues and co-create monitoring plans.
4. A systems monitoring and reporting framework that tracks not only engagement, quality, inclusion, impact, and transitions into employment, but also measures relational outcomes such as trust-building, empowerment, and integration of indigenous and local knowledge systems.
5. A participatory feedback and communication mechanism, ensuring that citizen-generated data is visualised (e.g., through the Digital Twin) and acted upon, with transparent reporting to communities on how their contributions inform management decisions.

Feedback and Adaptation

A citizen science water resources monitoring framework is not static; it must evolve in response to changing pressures, community needs, and monitoring and management priorities. Continuous feedback and adaptive management are essential to maintain relevance, improve performance, and strengthen trust among all stakeholders. Two-way feedback loops, where contributors and managers are co-engaged in decision-making, are critical for legitimacy, accountability, systems relevance and resilience, and sustained engagement (McKinley et al. 2017, Graham et al. 2024b, Mickelsson et al. 2024, Russell et al. 2024). For example, managers might make requests for resampling in under-represented areas, alerts on anomalies, and updates on management actions triggered by citizen-science data (Quinlivan et al. 2020b, Hegarty et al. 2021, Venkatesh and Velkennedy 2022, Elias et al. 2023, Wu et al. 2023), while citizen scientists might request access to incident reports, situated feedback on how to action trends and insights from their data, and increased capacity for monitoring locally important issues (Aceves-Bueno et al. 2015, Taylor and Taylor 2016, Taylor et al. 2022, Pattinson et al. 2023c). Digital platforms such as the CGIAR LIMCOM Digital Twin can automate parts of this two-way feedback system by generating notifications and visual dashboards that show where data have been used in decision-making. Integrated AI assistants, such as the Water Copilot (Vickneswaran et al. 2024), can summarise trends and answer natural language queries, further enhancing transparency.

From an adaptive management perspective, programmes should schedule regular reviews of protocols, training materials, and data workflows based on feedback from trainers, citizen scientists, and managers. This includes updating standard operating procedures when new tools or parameters are introduced, revising training content for clarity and inclusivity based on learner feedback, and adjusting incentivisation models to reflect participant preferences and emerging opportunities in green skilling (Lotz-Sisitka et al. 2022, Mickelsson et al. 2024, Russell et al. 2024). Analytics from the Digital Twin or other data reporting mechanisms should be used to identify gaps in spatial coverage, parameter consistency, and validation pass rates. Targeted interventions, such as refresher clinics or co-designed Impact Tasks for under-sampled sites, can also be deployed to improve representativeness and reliability. Adaptive management should ideally be documented and iteratively managed through co-engaged, transparent protocols. Publishing updates on programme websites or portals reinforces accountability and supports knowledge transfer to other basins.

Conclusions and Way Forward

Citizen science bridges critical data gaps, empowers communities by giving them agency within the water commons, builds trust, provides a potent platform for situated Action Learning, stimulates environmental education, and strengthens adaptive water governance by combining inclusive knowledge co-production with real-time insights for decision-making in complex, transboundary contexts (Bonney et al. 2009, Bela et al. 2016, McKinley et al. 2017, Fritz et al. 2019, Phillips et al. 2019, Pocock et al. 2019, Jørgensen and Jørgensen 2020, Sauermann et al. 2020, Fraisl et al. 2020, de Sherbinin et al. 2021, Dörler et al. 2021, Suman and Schade 2021, Tengö et al. 2021, van Noordwijk et al. 2021, Corburn 2022, Taylor et al. 2022, Ballard et al. 2024, Mickelsson et al. 2024). The conceptual model framework detailed here, co-developed and implemented in the Limpopo River basin of southern Africa, offers a structured, adaptable framework for integrating community-driven citizen science monitoring into basin-scale decision-support systems. Its loose six-step approach, complemented by continuous feedback and adaptive management, demonstrates that citizen science can move beyond isolated initiatives to become an integral part of formal, connected governance and stewardship water resource management networks.

Key Takeaways

1. Start with a strong foundation: Establishing a diverse, inclusive partner network and defining a clear data-to-action use case at the outset ensures that citizen science outputs are recognised and utilised by decision-makers.

2. Invest in capacity building: Training-the-Trainers programmes create local champions who can cascade skills and maintain quality, while embedding pedagogical approaches that foster environmental literacy and agency.
3. Design for inclusivity and interoperability: Community engagement must prioritise language access, low-data solutions, and offline functionality, while data workflows should align with FAIR principles relevant reporting standards or goals, such as SDG 6.3.2 reporting.
4. Integrate into decision-support systems: Linking curated citizen-science datasets to platforms such as river basin Digital Twins enables real-time visualisation, AI-assisted queries, and actionable insights for managers and communities alike.
5. Embed incentives and recognition: Incentivisation remains a critical consideration for citizen science programmes, particularly in the Global South where real barriers to participation persist despite strong community interest. A comprehensive approach should combine components such as formal credentials, secure digital identities linked to portable CVs, and impact-linked rewards that create pathways to green jobs. Beyond these, intrinsic motivators, such as agency, co-creation of knowledge, and visible influence on local water governance, are essential for long-term engagement. Sustainable financing models should underpin these structures.
6. Close the loop through feedback and adaptation. Two-way communication and iterative refinement sustain engagement, improve data quality, and ensure responsiveness to emerging challenges and opportunities.

Scaling to Other Transboundary River Basins

To implement this model framework for integrating citizen science into water resources monitoring and management in other contexts, the following recommendations are proposed:

- Contextualise the framework: Adapt the six-step model to local governance structures, cultural norms, and ecological priorities, while retaining its core principles of inclusivity, interoperability, and data-to-action pathways.
- Leverage existing regional platforms: Align citizen-science integration with basin organisations and regional initiatives, ensuring that data flows complement official monitoring and SDG reporting.
- Invest in digital infrastructure: Co-design and operationalise interoperable APIs and secure repositories from the outset, enabling seamless integration with decision-support systems and reducing retrofitting costs.
- Prioritise inclusivity through multilingual and low-bandwidth solutions: Translation of training and engagement materials and digital resources into local languages, combined with offline capture and lightweight content, is essential for diverse and inclusive participation.
- Embed locally relevant and co-created incentive structures linked to Green Economy pathways: Collaborate with youth employment programmes and digital credentialing platforms (e.g., Yoma) to connect citizen-science contributions and upskilling to sustainable job opportunities.
- Institutionalise adaptive governance: Formalise feedback loops and adaptive management protocols within basin organisations, ensuring that citizen science remains dynamic and responsive to changing environmental and socio-economic conditions.

The Limpopo River basin model demonstrates that citizen science, when digitally enabled and institutionally anchored, can transform water governance from the ground up. Scaling this model to other transboundary basins will require financial investment in, and commitment to, inclusivity, capacity building, innovation, and strong partnerships between communities, basin organisations, and global knowledge networks. However, by doing so, citizen science can become a cornerstone of resilient, participatory integrated water resources monitoring and management.

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