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Smart Water Stewardship Through Participatory Digital Monitoring

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Abstract

Effective water stewardship requires timely information about water quality, emerging contamination, infrastructure failures, local water-use conditions, and community concerns. Conventional professional monitoring remains essential, but its spatial and temporal coverage may be constrained by personnel, equipment, laboratory capacity, and monitoring frequency. This study develops a participatory digital monitoring framework that combines low-cost sensing, citizen observations, mobile reporting, data-validation procedures, institutional datasets, and transparent response mechanisms to support smart water stewardship. Because no primary field dataset was supplied, the research was designed explicitly as a simulation-based methodological study. A reproducible synthetic dataset representing 150 hypothetical community water-monitoring units was generated across three levels of participatory digital integration: low, moderate, and high. Five operational dimensions were evaluated: digital data completeness, validation rate, community engagement, response time to identified anomalies, and anomaly-resolution rate. These dimensions were additionally integrated into a Water Stewardship Performance Index (WSPI).

The simulation demonstrated a systematic improvement as participatory digital integration increased. Mean data completeness increased from 59.4% under low integration to 91.9% under high integration, while validated observations increased from 52.8% to 87.9%. Community engagement increased from 47.3% to 83.0%, and the mean anomaly-resolution rate increased from 45.8% to 86.4%. Simulated response time decreased from 15.2 hours to 4.6 hours. Consequently, the mean WSPI increased from 49.5 to 86.6. One-way analysis of variance confirmed strong internal separation among the deliberately parameterized scenarios, while repeated Monte Carlo analysis preserved the expected performance ordering across 500 simulation runs. The findings should not be interpreted as measured impacts from actual communities. Instead, they demonstrate how an integrated participatory-digital architecture could be evaluated in future empirical studies. The proposed framework emphasizes that smart water stewardship depends not merely on collecting more data but on validating information, connecting citizen-generated observations with professional monitoring, responding visibly to detected problems, and returning useful information to participating communities.

Keywords: smart water stewardship; participatory monitoring; citizen science; digital water monitoring; water quality; Internet of Things; community-based monitoring; water governance; low-cost sensors; environmental monitoring

1. Introduction

Water stewardship increasingly requires information systems capable of detecting environmental change at spatial and temporal scales that conventional monitoring programs may not always cover continuously. Professional laboratory measurements and regulatory monitoring remain fundamental to water governance, yet research on citizen science has shown that community participation can supplement formal monitoring by expanding observations, identifying locally important conditions, and generating environmental information across additional locations and time periods.

Njue and colleagues, in their review of hydrological citizen science, concluded that crowdsourced monitoring can contribute to hydrological knowledge and potentially support water-resource governance, while Quinlivan, Chapman, and Sullivan identified citizen science as a potentially useful complement to monitoring associated with Sustainable Development Goal 6.3.2. Digital technologies create an additional opportunity because low-cost sensors, smartphones, wireless networks, geospatial interfaces, and web dashboards can convert intermittent participation into more continuous and structured monitoring processes.

Recent community-led continuous-monitoring research nevertheless demonstrates that technology alone does not guarantee effective monitoring; calibration, maintenance, training, technical support, interpretation, communication, and long-term ownership remain essential. This study therefore conceptualizes Smart Water Stewardship not as automated sensing alone but as a socio-technical system in which digital measurements, citizen observations, data-quality controls, institutional knowledge, and management responses are deliberately connected. A simulation-based Water Stewardship Performance Index is developed to examine how stronger participatory-digital integration could influence monitoring completeness, validation, community participation, response speed, and problem resolution.

2. Literature Review

2.1 Citizen Science and Community-Based Water Monitoring

Citizen participation in environmental monitoring has evolved from occasional volunteer sampling toward more structured models involving community organizations, scientific institutions, public agencies, and digital platforms. Jollymore and colleagues demonstrated that participant perspectives influence the interpretation and production of citizen-generated water-quality information, emphasizing that data quality cannot be separated completely from monitoring design and participant experience. Studies of community-based monitoring have similarly emphasized that data become most valuable when they connect to actual management and policy processes rather than remaining isolated monitoring outputs. Carlson and Cohen's investigation of Canadian community-based water monitoring specifically examined the relationship between citizen monitoring and government-led water initiatives, demonstrating the importance of institutional recognition and pathways through which community evidence can influence decisions.

Citizen monitoring has also demonstrated the potential to extend spatial coverage. Thornhill and colleagues used citizen-science information to prioritize local action for water-quality improvement across metropolitan areas in China, illustrating how locally generated observations can contribute to geographically differentiated management. Citizen-led groundwater monitoring in Lebanon likewise demonstrated that trained participants could contribute to water-quality assessment under a structured research framework.

The literature nevertheless cautions against treating citizen-generated data as automatically equivalent to professional measurements. San Llorente Capdevila and colleagues identified participant characteristics, institutional characteristics, funding, communication, and supporting structures among the principal factors influencing successful water-quality citizen-science projects. Their review therefore suggests that successful participatory monitoring depends on the design of the monitoring institution as much as on the availability of sampling tools.

Walker, Smigaj, and Tani extended this discussion by examining benefits and potential negative consequences for participants and communities. Their review showed that participation may produce learning and community benefits, but it may also demand substantial time and effort and should not be assumed to benefit communities automatically.

More recent evidence further emphasizes institutional capacity. Dominguez-Rendón, Villada-Canela, and Muñoz-Pizza reviewed citizen water-quality monitoring initiatives and found that professionalization of citizen monitors, collaboration agreements, technical support, and recognition by institutions are important for strengthening community water organizations.
These findings support a central principle of the present study:

2.2 Digital Monitoring and Low-Cost Water Intelligence

Digital monitoring offers a mechanism for increasing the temporal frequency of water observations. Internet-connected sensing systems can continuously record parameters such as temperature, pH, conductivity, total dissolved solids, turbidity, or dissolved oxygen, depending on sensor configuration and monitoring objectives However, low-cost sensing introduces questions concerning calibration, sensor drift, fouling, maintenance, communication failures, and measurement uncertainty. Contemporary reviews of Internet-of-Things applications in water-quality monitoring therefore emphasize both their promise and the practical maturity limitations of deployed systems.

Ramírez, van Meerveld, and Seibert reviewed citizen-science approaches used for water-quality measurements and found considerable methodological diversity across citizen-monitoring studies. Their work reinforces the importance of matching measurement methods with intended monitoring objectives and explicitly evaluating strengths and limitations of different approaches.The possibility of integrating continuous sensors with citizen science is particularly relevant. Starkey and colleagues examined community-led continuous water-quality monitoring through pilot experiences in Taiwan and the United Kingdom. Their study found that continuous community-led monitoring can produce locally relevant information, but technical burdens, maintenance, training, costs, responsibilities, and capacity remain significant determinants of whether communities can sustainably lead these systems.

Digital systems can also improve access to monitoring results. Georgantas and colleagues developed a low-cost LoRa-based water-quality monitoring system integrating sensor stations with an information system for collecting and visualizing measurements. Their study demonstrates the technical feasibility of combining low-cost sensors, long-range communications, and web-accessible information while also emphasizing the importance of correcting and validating low-cost sensor measurements.These studies suggest that digital monitoring should not replace established laboratory and regulatory systems.

Its stronger role is to expand observation, support early identification of potential anomalies, prioritize professional investigation, and create better communication between communities and institutions.

3. Research Gap

Despite substantial research on citizen science and increasingly sophisticated work on digital water-quality sensors, several gaps remain between the two domains.First, citizen-science studies frequently emphasize participation, sampling, environmental education, or local knowledge, while sensor-system studies frequently emphasize hardware, communication protocols, measurement accuracy, energy consumption, or cloud connectivity. The integration of these technological and participatory dimensions into a single stewardship-performance framework remains comparatively underdeveloped.Second, collecting additional data does not guarantee improved water governance.

Citizen observations may remain unused when formal organizations do not recognize their validity or when mechanisms for institutional response are absent. Evidence from community-based monitoring has repeatedly identified the connection between data collection and formal decision-making as a critical issue.Third, digital water platforms may emphasize data acquisition without sufficiently measuring whether detected anomalies are actually investigated and resolved.Fourth, community participation is often measured through volunteer numbers or sampling frequency, whereas meaningful stewardship also requires feedback, transparency, continued participation, trust, and the ability to influence decisions.

Fifth, comparatively few frameworks jointly evaluate:

- monitoring completeness;
- validation quality;
- participatory engagement;
- institutional response speed; and
- resolution of identified water problems.

The present study addresses these gaps through the proposed Participatory Digital Water Stewardship Framework (PDWSF) and an associated Water Stewardship Performance Index (WSPI).

4. Novelty and Proposed Contribution

The proposed model differs from conventional water-monitoring systems that emphasize sensor performance or citizen participation as separate functions. Instead, it integrates five operational layers into a coordinated stewardship process. The Observation Layer combines low-cost sensors, manual water testing, citizen photographs, location-tagged reports, and local observations to capture diverse forms of water-related information. The Digital Integration Layer connects these observations through mobile applications, web portals, wireless communication systems, databases, and geospatial referencing. The Validation Layer strengthens information reliability through automated range checks, calibration procedures, duplicate-measurement screening, expert review, reference-station comparisons, and laboratory confirmation when required. Together, these layers create a structured pathway through which community-generated observations can be transformed into credible and actionable environmental information.

The remaining two layers extend the framework from information collection toward practical environmental response. The Response Layer enables responsible agencies and water managers to receive notifications, prioritize anomalies, conduct investigations, initiate corrective actions, and document case closure. The Community Feedback Layer then supports transparency by publishing validated information, explaining management responses, communicating uncertainty, and providing opportunities for continued citizen participation. The principal novelty of the model is therefore its shift from "smart monitoring" toward "smart stewardship." Monitoring primarily asks what is happening within the water system, whereas stewardship additionally considers who possesses relevant knowledge, whether the information is reliable, who is responsible for responding, how quickly action occurs, whether the problem has been resolved, and whether participating communities receive meaningful feedback. This broader perspective positions citizens not merely as data providers, but as active participants in a continuous cycle of observation, verification, response, and environmental accountability.

5. Research Objectives

The principal objective of the study is to develop a transparent framework for evaluating the potential contribution of participatory digital monitoring to smart water stewardship. More specifically, the research seeks to examine whether progressively stronger integration among digital monitoring, citizen participation, data validation, and institutional response produces distinguishable stewardship-performance profiles under controlled simulation conditions. A second objective is to formulate a Water Stewardship Performance Index that moves beyond the conventional measurement of data quantity by incorporating data completeness, validation quality, community engagement, response speed, and anomaly resolution. The study also seeks to clarify the functional roles of low-cost sensors and community-generated observations within a broader water-governance architecture rather than representing either source as a substitute for professional monitoring. An additional objective is to develop a practical monitoring-to-action feedback cycle that can guide future implementation by municipalities, watershed organizations, water utilities, research institutions, or community water groups. Finally, the study establishes a reproducible synthetic baseline from which future empirical investigations can test whether the modeled relationships occur in operational water-management environments.

Research Questions

RQ1: How can participatory and digital water-monitoring functions be integrated within a unified stewardship framework?

RQ2: How does increasing participatory digital integration affect simulated monitoring-data completeness?

RQ3: Does stronger integration improve the modeled validation and resolution of water-related anomalies?

RQ4: How does participatory digital integration influence simulated institutional response time?

RQ5: Can a composite Water Stewardship Performance Index differentiate low-, moderate-, and high-integration monitoring scenarios?

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6. Research Methodology

6.1 Research Design

The study employs a quantitative simulation-based research design.

No field measurements, real community participants, actual water utilities, or genuine regulatory monitoring records were used.A synthetic dataset representing 150 hypothetical community water-monitoring units was generated.

The units were divided equally into three experimental conditions:

- **Low Participatory Digital Integration:** 50 units
- **Moderate Participatory Digital Integration:** 50 units
- **High Participatory Digital Integration:** 50 units

A fixed random seed of 20260811 was used to ensure reproducibility.

The purpose of the simulation was not to predict the magnitude of benefits that actual communities will obtain. Instead, it tested the internal behavior and analytical discrimination of the proposed framework.

6.2 Performance Indicators

Five principal operational indicators were simulated.

Data Completeness

Data completeness represents the percentage of planned monitoring observations successfully captured and available for analysis.

Validation Rate

Validation rate represents the percentage of citizen or sensor observations that successfully pass predefined quality-assurance procedures.

Community Engagement

Community engagement represents sustained participation in monitoring, reporting, interpretation, and local stewardship processes.

Response Time

Response time represents the modeled number of hours between recognition of a relevant monitoring anomaly and initiation of an organizational response.

Anomaly-Resolution Rate

Resolution rate represents the percentage of validated anomalies that subsequently receive documented corrective action or formal case closure.

6.3 Scenario Parameterization

Table 1: Simulation Design and Operational Assumptions

Indicator	Low Integration	Moderate Integration	High Integration	Interpretation
Planned data completeness	Mean 58%, SD 8	Mean 75%, SD 7	Mean 91%, SD 5	Continuity of usable monitoring information
Validation rate	Mean 54%, SD 9	Mean 72%, SD 7	Mean 88%, SD 5	Reliability after quality assurance
Community engagement	Mean 48%, SD 10	Mean 68%, SD 8	Mean 84%, SD 6	Sustained participatory involvement
Response time	Mean 16 h, SD 4	Mean 9 h, SD 2.5	Mean 4.5 h, SD 1.5	Time required to initiate response
Anomaly-resolution rate	Mean 45%, SD 9	Mean 67%, SD 8	Mean 86%, SD 6	Completion of corrective action

7. Participatory Digital Water Stewardship Framework

The Participatory Digital Water Stewardship Framework brings together diverse sources of environmental information to create a more comprehensive understanding of local water conditions. Low-cost sensors contribute frequent measurements, while citizen observations add contextual details and geographically distributed evidence that may not be captured through conventional monitoring. Mobile and web-based platforms support structured reporting, whereas utilities and public agencies provide professional monitoring results and operational knowledge.

Local communities further strengthen the framework by contributing experience-based information about recurring water problems, unusual changes, infrastructure performance, and events that are significant within their surroundings. By integrating these complementary sources, the participatory digital intelligence layer can validate, classify, and interpret observations before converting them into clearly defined stewardship priorities. The central contribution of the framework is therefore its movement beyond simple data generation toward coordinated interpretation, institutional response, and meaningful community action.

8. Results

The synthetic analysis showed a strong monotonic progression from low to high participatory digital integration.

Table 2: Simulated Water-Stewardship Performance

Performance Indicator	Low Integration	Moderate Integration	High Integration	High–Low Difference
Data completeness (%)	59.4	75.2	91.9	+32.5
Validation rate (%)	52.8	72.6	87.9	+35.1
Community engagement (%)	47.3	68.4	83.0	+35.7
Mean response time (hours)	15.2	9.0	4.6	−10.6 h
Anomaly-resolution rate (%)	45.8	66.2	86.4	+40.6
Water Stewardship Performance Index	49.5	69.6	86.6	+37.1

8.1 Monitoring Completeness

The mean data-completeness score increased from 59.4% under low integration to 75.2% under moderate integration and 91.9% under high integration.

The result reflects the simulation assumption that integrated digital systems experience fewer monitoring gaps because information is collected through multiple channels.However, data completeness alone cannot establish monitoring quality.A system could collect large quantities of unreliable information. Therefore, completeness was evaluated alongside validation.

8.2 Validation Performance

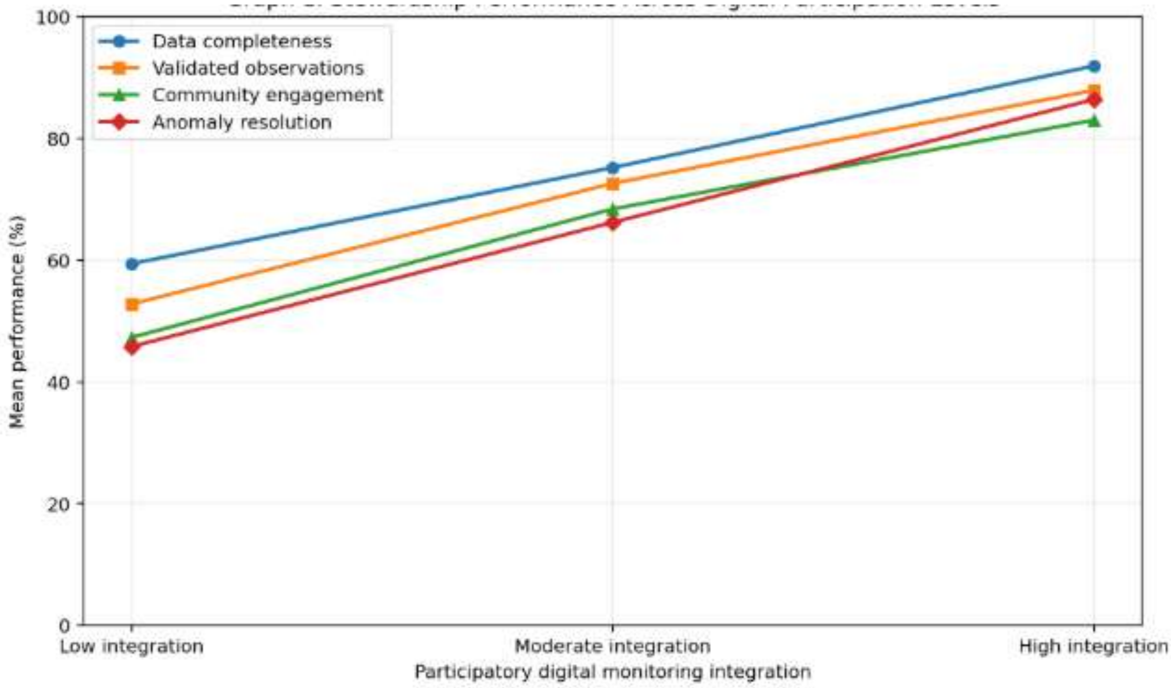
The mean validation rate increased from 52.8% to 72.6% and finally 87.9%.

The distinction between data acquisition and validation is particularly important for citizen science and low-cost sensing.Citizen-science literature emphasizes standard protocols, participant training, and quality-control procedures, while low-cost sensor research emphasizes calibration and correction.

The framework therefore does not assume that every submitted observation should automatically enter an official water database.Instead, observations can progress through different confidence levels depending on source, calibration status, consistency, duplication, expert review, and laboratory confirmation.

9. Graphical Analysis

Graph 1: Stewardship Performance Across Digital Participation Levels



The graph compares four percentage-based stewardship indicators across the three integration scenarios. Data completeness increased consistently with participatory digital integration.

Validation performance followed a similar trajectory.Community engagement demonstrated a substantial increase between low and moderate integration and continued improving under high integration.The greatest absolute improvement among the four graphically represented indicators occurred in anomaly resolution.

Key Finding:

The simulation indicates that the potential value of participatory digital monitoring lies not in any individual component but in the joint improvement of observation, validation, participation, and response.A technologically advanced monitoring platform with weak community engagement would remain incomplete.

Similarly, highly active community participation without validation procedures or institutional response pathways would generate information without consistently converting that information into stewardship outcomes.

10. Response and Resolution Performance

- One of the most important modeled changes involved institutional response time.
- Average response time decreased from 15.2 hours in the low-integration scenario to 9.0 hours in the moderate scenario and 4.6 hours under high integration.

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- This represents a simulated reduction of approximately 10.6 hours between the low- and high-integration scenarios.
- Anomaly-resolution performance simultaneously increased from 45.8% to 86.4%.
- The model therefore distinguishes between two related but different governance outcomes:
- Response means that a validated problem is acknowledged and investigated.
- Resolution means that an appropriate corrective process has been completed or formally documented.
- This distinction matters because a dashboard that generates rapid alerts does not necessarily improve stewardship if responsible organizations cannot investigate and resolve reported problems.

11. Discussion

The results support the conceptual proposition that smart water stewardship should be understood as a socio-technical governance process rather than a sensor-deployment project.

The high-integration scenario generated the strongest simulated performance because monitoring technology, citizen participation, validation, institutional response, and feedback were modeled as connected processes.

This interpretation is consistent with the broader citizen-science literature. Njue and colleagues argue that citizen science can support hydrological monitoring and ecosystem-service management while contributing to knowledge co-creation. However, the practical value of citizen-generated evidence depends substantially on how monitoring programs are designed.

11.1 From Data Quantity to Data Usability

One of the central findings is the need to distinguish data quantity from data usability.

A monitoring program could receive thousands of observations without creating reliable water intelligence.Ramírez, van Meerveld, and Seibert's review demonstrates that citizen-science water-quality methods differ substantially in their characteristics, strengths, and limitations. Consequently, digital platforms should store metadata describing measurement method, instrument, location, time, calibration status, participant training, and confidence level.Professional measurements and community observations should not necessarily be merged indiscriminately.

Instead, a tiered evidence architecture could classify data as:

screening information,validated community data,sensor-confirmed information,orregulatory-grade/laboratory-confirmed evidence.Such an architecture could preserve the value of rapid citizen observations without overstating their measurement certainty.

11.2 Participatory Monitoring as Distributed Intelligence

Community participation adds value partly because residents and local organizations observe water systems continuously through everyday experience.A resident may notice unusual odor, color, foam, recurring leakage, fish mortality, algal growth, infrastructure overflow, or changes occurring after specific rainfall events.Digital platforms can transform these observations into time-stamped and geolocated information.

Citizen participation can therefore function as a distributed early-observation network.However, distributed intelligence requires inclusion.A smartphone-only reporting platform may underrepresent populations with limited internet access, lower digital literacy, language barriers, disabilities, or limited trust in institutions.The system should consequently provide multiple participation channels rather than interpreting digital participation as synonymous with smartphone ownership.

12. Conclusion

This study developed a simulation-based framework for Smart Water Stewardship Through Participatory Digital Monitoring. The central argument is that effective digital water stewardship cannot be reduced to the installation of sensors or creation of a citizen-reporting application. A genuinely smart system must connect observation, participation, validation, interpretation, institutional response, corrective action, and community feedback.

A synthetic experiment involving 150 hypothetical community monitoring units demonstrated the internal behavior of the proposed framework across low, moderate, and high participatory digital integration. Data completeness increased from 59.4% to 91.9%, validation performance increased from 52.8% to 87.9%, community engagement increased from 47.3% to 83.0%, and anomaly resolution increased from 45.8% to 86.4%. Mean response time simultaneously declined from 15.2 hours to 4.6 hours. The composite Water Stewardship Performance Index consequently increased from 49.5 to 86.6.

These values are simulated and must not be interpreted as measured real-world effects.The study's primary contribution is methodological. It provides a structured way to evaluate whether digital monitoring systems actually progress from data collection to stewardship action.Participatory digital monitoring has the greatest potential when professional measurements and citizen knowledge are treated as complementary forms of evidence, when data quality is explicit, when responsibility for response is defined, and when communities can see how their participation contributes to the protection and sustainable management of water resources.

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