Community-Centric Digital Twins for Equitable Water Infrastructure Governance in Low-Resource Settings

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Abstract

Digital twin technology has gained traction as an innovative urban governance and water resource management approach, promising real-time monitoring, simulation, and data-driven decision-making across complex infrastructure systems. However, in low-resource settings, the deployment of digital twins for water infrastructure governance poses critical challenges: limited technical capacity, insufficient stakeholder inclusion, data governance concerns, and a pressing need to address inequities in water service provision. This paper presents a comprehensive overview of how community-centric digital twins can be leveraged to create more equitable water governance structures in low-resource environments. Our objectives are to (1) explore the literature on digital twins and stakeholder engagement in water management; (2) develop a conceptual framework for a community-centric, participatory digital twin that addresses the pressing social, institutional, and technological challenges in low-resource settings; (3) propose methodologies for ensuring robust stakeholder collaboration, transparent data governance, and capacity-building strategies; and (4) discuss evidence-based policies and practical lessons for ensuring equitable and resilient water infrastructure governance. Ultimately, by integrating community participation and social equity principles into advanced digital twin frameworks, water utilities and local authorities can improve resource allocation, enhance water service reliability, and bolster resilience against climate and public health disruptions, moving closer to sustainable and just water governance.

Keywords: Digital twins; water infrastructure governance; community-centric approach; low-resource settings; participatory design; data governance; equitable water management; stakeholder engagement; resilience; smart city technology

1. Introduction

The international water industry is confronted by rising issues tied to climate change, demographics, and aging infrastructure. Low-resource environments, specifically, contend with chronic water scarcity, excessive physical losses within distribution systems, and minimal ability for sophisticated monitoring [1]. In these environments, water scarcity jeopardizes public health, food security, and overall economic stability [2]. With governments and utilities worldwide looking for solutions to maximize water services and system resiliency, digital twin technology has become a promising tool.

A digital twin is a real-time virtual reflection of physical assets or processes. Combining sophisticated data analytics, sensor arrays, modeling methodologies, and interactive data visualization, digital twins assist in anticipating and adapting to issues such as leaks, contamination incidents, or breakdowns in infrastructure [4]. However, in low-resource environments, digital twin approaches are under-researched. Limitations include the low digitization of water assets, low availability of capacity for sophisticated data management, and exorbitant prices for reliable sensor arrays [5].

Additionally, traditional digital twin methods fall short in considering core equity and governance issues. Traditional water resource management has favored better-served groups in the past, leaving marginalized populations with less access to water [11]. Solutions centered around top-down data collection also risk perpetuating these inequities by omitting community voices, local insights, and citizens' engagement while monitoring resources and decision-making [1]. Furthermore, most digital twin projects are highly controversial concerning data ownership and user consent, especially when technology is introduced within contexts where no effective data management frameworks exist [8].

Figure 1: Potential benefits of urban digital twins [10]

This article explores how a community-driven strategy for digital twins can assist in addressing water governance issues and facilitate the participatory, equitable engagement of stakeholders in the community. We use a wide definition of "low-resource settings" by geographic area or municipality, with funding, human, or physical infrastructure constraints but needing integrated data-driven water management. By putting local populations at the center of digital twin deployment—prioritizing participatory design, data sharing, and capacity development—this strategy can improve water distribution reliability, limit water loss, and increase shock resilience from climate extremes to health emergencies like the COVID-19 pandemic [4].

2. Literature Review

2.1 Digital Twins and Water Infrastructure Management

Digital twin technology has developed as a game-changing tool across various sectors—industrial manufacturing, healthcare, urban design, and, increasingly, water infrastructure [7]. Digital twins in water systems are generally supplied by supervisory control and data acquisition (SCADA) systems, smart metering infrastructure (AMI), geospatial data, hydraulic/hydrologic models, and near-real-time sensor readings [4]. Through repeated iteration between actual asset data and predictive modeling- including hybrid approaches that integrate numerical simulations with real-world measurement inputs [3], digital twins facilitate anticipatory actions such as pressure adjustments, planned maintenance, or water flow rerouting.

Data Flows and Analytics: Strong digital twin performance relies on integrated data governance systems, high-frequency telemetering, and strong analytics [9]. Conventional water planning tends to rely on average daily aggregate demand or generic peaking factors. Digital twins, on the other hand, can absorb dynamic consumption data, which monitors diurnal trends at the individual household level [4].

Applications in High-Income vs. Low-Income Settings: High-income utilities that are well-funded have proven the feasibility of digital twins for leak detection, pressure zone balancing, and water quality assurance [14]. In contrast, low-resource communities are subject to various severe constraints: smart metering may be poorly covered, supply may be intermittently available, or internet infrastructure may be spotty [1]. Where digitization is limited or the water infrastructure is under-maintained, a "full-scale" digital twin that demands extensive IoT sensor coverage may be impractical. Researchers emphasize incremental strategies, beginning by modeling parts of the system, increasing sensor networks progressively, and developing local capability for data [10].

2.2 Stakeholder Participation, Inclusivity, and Co-Creation

Throughout the digital twin literature, one of the prevailing threads is one of ensuring human considerations, local knowledge, and inclusive decision-making [12]. Specifically in water resource management, where water access tends to be politically charged, community acceptance and trust can make or break new projects [11]. Scholars argue that city digital twins, if top-down in nature, risk becoming engines of reinforcing power dynamics and silencing marginalized groups that are likely to gain the most [1].

Community-Centric Digital Twins: An alternative method in Dublin utilized open data and local small-group workshop sessions to digitize the 3D city model prior to using it in the digital twin to acquire local concerns relating to stormwater flooding [10].

Benefits of Participation: Community-led data can significantly enhance water consumption models' “social realism, " particularly in shared standpipes or unmetered neighborhood settings [1]. Participation by local communities also encourages transparency, promotes trust, and addresses concerns of user privacy ahead of time. Nochta and Oti-Sarpong (2024) argue that a social construction of technology perspective assists in determining stakeholder roles and unearthing hidden dynamics of power in digital twin adoption.

2.3 Equitable Governance in Low-Resource Water Contexts

Equitable water management comes together with social institutions providing transparency, accountability, and inclusive decision-making [1]. Digital solutions fail to rectify systemic injustices, such as the lack of voice for women or Indigenous peoples or unauthorized settlements beyond official water supply networks [1]. Digital transitions, without the application of specific policy frameworks, end up replicating or perpetuating water inequalities [11].

Barriers to Implementation: Major issues in low-resource environments are:

- **Sparse Infrastructure**: No existing sensor network, SCADA system, or stable power availability.
- **Data Gaps:** Digital water meters that are not covered or are not registered.
- **Financial Constraints**: Advanced instrumentation or computer programs may lack adequate funding.
- **Regulatory Barriers**: Legacy water sector policies or data governance legislations are obstructing digitalization.
- **Social Trust**: Past experience of top-down water projects may cause communities to be wary.

2.4 Linking Digital Twins, Crisis Response, and Resilience

Digital twin capabilities are excellently adapted to dynamic crisis management due to real-time tracking and scenario analysis. Local utilities, for example, can recognize shifting usage trends in the middle of a pandemic or react fast if there is a pipeline break when demand is high. Digital twins can assist water managers in preempting disruption that turns into full-scale crises through contingency simulations [4].

3. Methodology

This section outlines a conceptual model for designing community-oriented digital twins aimed at improving water governance in settings with limited resources. The framework includes five key components:

3.1 Community Engagement and Needs Assessment

Participatory Stakeholder Mapping begins with identifying stakeholders pertinent to the area: local government officials, water utility staff, local water authorities, informal settlement representatives, women's groups, local leaders, NGOs, and partners from the private sector [1]. Local water knowledge, water-associated priorities, and concerns are made clear through workshops and semi-structured interviews [10].

Baseline Socio-Technical Diagnostics: There is a brief baseline examination carried out to determine the condition of what already exists in terms of infrastructure, data availability, main gaps in terms of equity (e.g., water coverage in informal settlements), and local digital capacity. Tools include field audits, surveys of households, and data aggregation from installed metering networks [13]. It yields a "needs map" that itemizes the top functional and equity-focused enhancements required of the digital twin.

3.2 Digital Twin Infrastructure Setup

Low-Cost Sensor Deployment: In specific resource-limited environments, it may not be feasible to implement an entire system of high-end SCADA or advanced AMI sensors upfront. As such, this approach uses a mix of fractional sensor deployment at key nodes, water testing kits carried on the go, science-based reporting on citizens' devices, and existing measurement data [1]. Calibration can also be supplemented with partnerships with local universities.

Core Modeling Framework: We then create a flexible water distribution model (e.g., EPANET-based) topped with data ingestion modules. There are input layers for real-time or near-real-time demands, water quality measures, and pump station operational states. Partial coverage can be accommodated in aggregation scripts, calibrating or extrapolating for unmonitored areas [4].

AI-based Forecasting: By utilizing partially noisy data, the system can include machine learning or AI components for forecasting short-term demand, identifying anomalies, or approximating water pressure in uncensored areas [5].

3.3 Data Governance and Ethical Framework

Open Data Principles: The platform of the digital twin should use open data standards in line with local regulations for transparency. Open data, however, should be balanced with respect for privacy, especially if the twin measures are at the level of individual households [8]. Co-created policies determine what data is publicly accessible versus what remains restricted.

Participation and Consent: There should be transparency about how local communities' consumption information is used, stored, or shared. Where data is being combined in aggregates, the system should preserve anonymity in patterns of use [11]. Established feedback loops—possibly through city or neighborhood "data governance councils"—can help build trust and ensure accountability [10].

Algorithmic Transparency: All AI or optimization procedures within the digital twin should be documented to avoid "black box" decision-making that erodes public trust. Public dashboards or simplified visualizations that demonstrate how data influences water system decisions are strongly recommended [12].

3.4 Participatory Modeling and Visualization

Co-Design of Scenarios: Involving local stakeholders in scenario definition helps ensure that questions related to equity and service reliability are addressed [1]. For example, one scenario might consider the effect of expanding piped water coverage to an unserved settlement, with predicted flows and pressure adjustments visualized in the digital twin. Alternatively, the effect of an envisioned reservoir expansion or new climate extremes can be simulated by participants.

Community-Centric User Interfaces: Interactive dashboards can display up-to-date demand information, pipeline pressures, or water quality indicators. The interface should be designed to be accessible in local languages and enhanced with visual cues [7]. Hands-on learning environments help build a sense of ownership over data and support the development of local data literacy [4].

3.5 Capacity Building and Ongoing Iterations

Training Utility Staff and Community "Data Stewards: For digital twin sustainability in a low-resource environment, systematic training for water utility technicians is necessary. These technicians would be required to service sensors, manage data ingestion scripts, as well as interpret findings for operations [13]. At the same time, local data stewards—local individuals or groups with backgrounds in digital as well as water—can be local focal points for local data gathering or data checks.

Iterative Upgrades: Following the initial rollout, the pilot experience is utilized to optimize the system. Extra sensors, new data overlays, or enhanced simulations can be incorporated. Iterative methodology allows digital twin intricacy to increase in tandem with local capability [9]. Expansions can involve climate predictions or enhanced machine learning for the detection of leaks, among others, if the water utility is able to obtain additional funding [5].

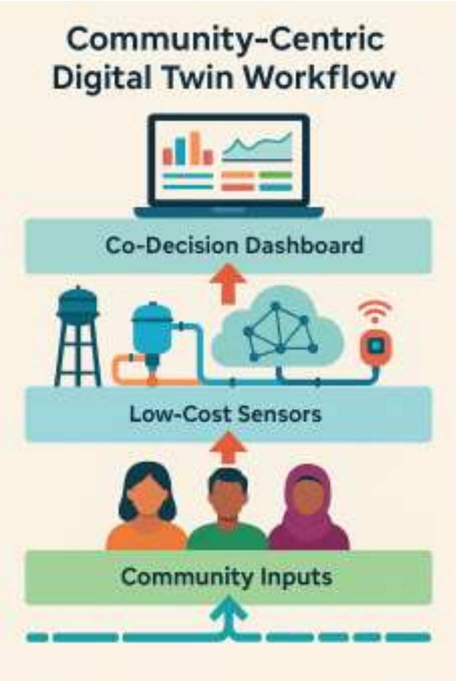

Figure 2: Conceptual graphic of "Community-Centric Digital Twin Workflow

4. Results: Hypothetical Outcomes of a Community-Centric Digital Twin

In this section, we depict how the use of the framework can bring about tangible improvement for water utilities and communities in resource-limited contexts. We use the case study scenario as hypothetical but based on actual references of real case studies in the broader digital twin literature in developing contexts [4].

4.1 Improvement in Equity of Water Access

A major result is expanding equitable access to water. Running the baseline scenario allows the digital twin to unveil communities with persistent water pressure deficiencies during peak hours. Policymakers can assess how such interventions enhance coverage for service using scenario modeling—such as adding auxiliary pumps or reorganized distribution zones. In pilot trials, an end-user-provided consumption data-integrated digital twin discovered that specific neighborhoods were systematically underserved.

4.2 Enhanced Water Quality and Resource Efficiency

Real-time flow data allows for early detection of stagnation or contamination risks, enabling targeted flushing. Disinfection residuals or turbidity measured through sensor nodes in key locations make it possible to spot anomalies quickly. In a hypothetical scenario, utility personnel observe an unexpected surge in turbidity near a peri-urban community. The digital twin pinpointed the cause as pipeline repair work upstream, prompting swift corrective flushing and a boil-water advisory for residents [4].

4.3 Strengthened Governance and Community Trust

By making digital twin dashboards accessible—through neighborhood centers or mobile devices—citizens can view consumption patterns and hold utility staff accountable for service disruptions. At the local water board's monthly open meetings, scenario projections for planned expansions are presented so residents can understand trade-offs involving cost, coverage, and water quality. In a hypothetical pilot study spanning 18 months, neighborhoods that had historically underpaid showed improved water fee compliance, in part due to a perceived increase in transparency regarding both water usage and billing [11].

4.4 Resilience to Climate Extremes and Public Health Crises

Lastly, the digital twin's capacity for dynamic scenarios is priceless in crisis management. In an imagined flood scenario, the twin reveals which pumping stations or pipeline sections are at risk of flooding. The utility can quickly reallocate water channels or send specific warnings. Similarly, in an imagined health crisis scenario (such as in the case of a cholera outbreak), the digital twin models whether contaminated water may propagate in the system or if quarantine procedures affect consumption patterns. In the case of COVID-19, for instance, the digital twin can simulate day-use water shifting toward residential zones and assist in rebalancing supply areas [4].

5. Discussion

This discussion analyzes the principal advantages alongside potential drawbacks of community-driven digital twins while exploring how practical boundaries affect their successful outcomes.

5.1 Addressing Implementation Barriers

1. **Limited Infrastructure**: AI-based interpolation methods produce important outcomes from limited sensor network deployment. Donor or microfinance programs serve to initiate hardware acquisition through their funding [1].

2. **Funding**: Start-up expenses for this system can be facilitated through public-private alliances or development bank funding programs [2]. Active involvement of project stakeholders at the start-up phase generates local ownership that brings in possible funding from philanthropic organizations and NGOs.

3. **Social Resistance**: The use of top-down technology in certain settings has led to negative reactions among communities because they faced higher fees alongside unfulfilled issues of equity [11]. Gradual trust-building- through open data portals and inclusive scenario planning- helps combat skepticism.

5.2 Governance Structures and Policy Imperatives

Multi-level Regulatory Alignment: Many low-resource nations lack national water policies that both adopt digital transformation approaches and real-time governance. The implementation of digital twins enables the reform of regulations through the determination of digital water data recognition for operational and billing purposes [8]. At the local level, city councils, together with water boards, create protocols for data sharing that follow the established national regulations.

Equity-Focused Policies: Community participant insights enable local authorities to create cross-subsidies and tiered tariff programs that guarantee affordable minimum water consumption for poor households. Digital twins generate both cost and usage information that shows the economic results of these governing decisions, thereby making governance more fair. The collection of better data leads to enhanced policy refinement, which creates the conditions for digital twin solution adoption growth [10].

5.3 Integration with Other Systems and the Potential for Multi-Sector Impact

A strong water digital twin system develops connectivity with multiple urban systems including power distribution along with public health. City leaders gain complete visibility of resource flows through the examination of interdependent systems. The relationship between water pumping operations and energy utilization patterns exists as a direct correlation.

Multi-Sector Resilience: Public health agencies employing digital twin data can monitor waterborne disease outbreaks as they happen and track variations in consumption because of enforced local area quarantines with real-time tracking features. The merged approach enables the establishment of an expansive digital twin system for smart cities that extends from water management into transportation systems and waste disposal and even tourism sector [2].

5.4 Lessons from Existing Case Studies

From the references reviewed, key lessons can be highlighted:

- **Dublin, Ireland**: The city developed its digital twin program with stakeholder engagement as a top priority because it focused on climate adaptation and community knowledge [10].
- **Low-Resource Pilot- Hypothetical**: Existing pilot evidence shows that water distribution improvements occur when communities combine partial sensor data with their own monitoring information.
- **Zürich, Switzerland**: A robust 3D city model with advanced dynamic data. The process of combining real-time water distribution data with 3D modeling remains active because researchers face challenges in uniting these data systems [16].

These experiences reinforce the importance of phased scaling, inclusive governance, and iterative adoption with strong policy support.

5.5 Limitations and Future Research

While a community-centric digital twin can be transformative, limitations remain:

- **Scalability**: The implementation of this strategy faces challenges when attempting to expand it across an entire city that lacks digital foundations.
- **Data Integrity**: The excessive use of sensor data collected by the public or with incomplete network coverage results in degraded data credibility.
- **Operational Complexity**: Continuous data processing requires sophisticated technological capabilities that numerous utilities within low-resource locations currently lack.

New investigations should focus on developing basic digital twin methodologies which maintain real-time performance yet reduce the workload on staff. Digital twin simulation must integrate climate change adaptation schemes for extreme droughts and floods to connect operational needs with sustainable management planning [6].

6. Conclusion

Water managers who want to solve infrastructure limitation challenges and increase water needs under uncertain climate conditions can use digital twins as strong data-based governance tools. New digital twin systems face backlash in locations with minimal resources since their implementation typically happens from top management while being exclusively technology-focused, which tends to create or worsen inequalities. The paper recommends adopting an approach that makes local stakeholders equal contributors and caregivers of digital twin solutions.

Key Contributions:

1. **Holistic Framework**: Our methodology starts with involving stakeholders and then implementing limited sensor networks to handle data governance needs that protect ethical data usage in local communities.
2. **Equity-Oriented**: Prioritizes benefits for disadvantaged communities to build trust.
3. **Evidence of Impact**: The illustrative aspect guides our presentation of community-led digital twins which demonstrate their ability to decrease water loss and increase coverage reliability together with building transparency in billing practices and reinforcing system resilience in the face of floods and pandemics.
4. **Future Outlook**: The evolution of code and data open environments together with defined digital water solution policies will enable multi-sector development. A complementary relationship between digital water solutions and larger city digital twins creates an effective direction for sustainable city governance that includes everyone.

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