# Innovative Operating Methodology for Continuous Water Supply in Georgian Regions: Digital Twins and IoT Integration

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**bstract**
This research develops and validates a comprehensive, data-driven operational methodology designed to ensure continuous and secure water supply in the regional districts of Georgia. Addressing the systemic inefficiencies of aging infrastructure—specifically high Non-Revenue Water (NRW) losses and energy-intensive pumping—the study introduces an integrated framework centered on the "Digital Twin" concept. By establishing a real-time bidirectional link between physical assets and a dynamic hydraulic model, the methodology leverages a Wireless Sensor Network (WSN) to capture high-fidelity data on pressure, flow, and quality parameters (turbidity, pH, residual chlorine, and electrical conductivity).
The core innovation involves the application of Artificial Intelligence (AI) and Machine Learning (ML) algorithms to transition from traditional reactive maintenance to proactive operational management. These algorithms function as "virtual sensors," enabling the prediction of system behavior in nodes where physical sensing is cost-prohibitive. The methodology was empirically tested within the Dedoplistskaro municipality, a region characterized by complex topography and significant geodesic elevation shifts.
Key results demonstrate that the integration of EPANET-based hydraulic simulations with real-time IoT data reduced the response time for contamination detection from a 24-hour laboratory cycle to less than 10 minutes. Furthermore, the implementation of automated pressure management and leak-detection algorithms led to a 15-20% reduction in water losses. The findings provide a scalable technological roadmap for the digital transformation of Georgia's water sector, offering a universal solution for optimizing energy consumption, ensuring chemical safety

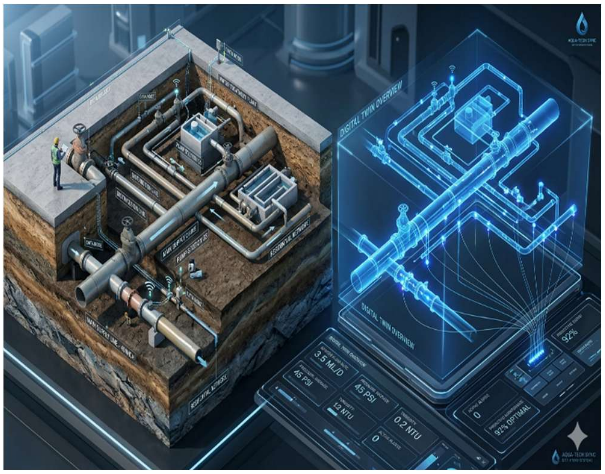
through automated dosing, and establishing a robust foundation for "Smart Water Grid" implementation in developing regional infrastructures.

**Keywords:** Digital Twin, Water Supply Systems, IoT (Internet of Things), Artificial Intelligence, Georgia Regions, EPANET, Hydraulic Modeling, Smart Water Management

## 1. Introduction

The sustainable management of water resources has emerged as one of the most critical global challenges of the 21st century, exacerbated by rapid urbanization, climate change, and the increasing complexity of urban infrastructure. In the Republic of Georgia, particularly within its diverse regional districts, water supply systems face a unique set of systemic vulnerabilities. These include aging pipe networks, significant volumes of Non-Revenue Water (NRW) due to undetected leakages, high energy consumption in pumping stations, and a historical reliance on reactive, manual operational practices.
Traditional water management methodologies in these regions are primarily characterized by intermittent monitoring. Water quality assessment typically relies on periodic manual sampling and subsequent laboratory analysis, a process that can take anywhere from 24 to 48 hours to produce actionable results. In the event of a contamination incident, this time lag

poses a severe risk to public health. Furthermore, hydraulic management is often based on static models that fail to account for the dynamic, real-time fluctuations in consumer demand and the varying discharge rates of water sources.



This research addresses these gaps by proposing a paradigm shift from passive observation to proactive, automated operation through the integration of the "Digital Twin" framework. A Digital Twin is not merely a static 3D model; it is a dynamic virtual representation of the physical water network, continuously synchronized with real-time data via the Internet of Things (IoT) and Wireless Sensor Networks (WSN). By embedding physical, chemical, and optical sensors throughout the infrastructure, the system gains the ability to "feel" and "see" hydraulic and qualitative changes as they occur.

The primary objective of this study is to develop a comprehensive methodology that enables:

Real-time Synchronization: Bridging the gap between physical infrastructure and digital hydraulic models (such as EPANET) to reflect current system states.

Predictive Analytics: Utilizing Artificial Intelligence (AI) to forecast potential failures, identify hidden leakages through pressure-flow anomalies, and simulate "what-if" scenarios for emergency planning.

Automated Safety Protocols: Implementing intelligent feedback loops for automated chlorine dosing and rapid isolation of contaminated zones, thereby minimizing the "human factor" and response latency.

By applying this methodology to the Dedoplistskaro regional network—a system defined by its challenging topography and variable water quality—this research demonstrates how digital transformation can ensure a resilient, energy-efficient, and continuous water supply, providing a scalable model for the modernization of Georgia’s regional utilities.

## 2. Main part

The research methodology is structured as a multi-layered technological framework designed to bridge the gap between physical infrastructure and digital management. The implementation was carried out in the Dedoplistskaro municipality, a region that presents a "worst-case scenario" for water utilities due to its extreme topographic variations and aggressive groundwater chemistry.

To achieve real-time visibility, a Wireless Sensor Network (WSN) was architected. This involved the strategic installation of high-precision sensors at three critical points of the infrastructure:

Headworks and Pumping Stations: Sensors monitor water source discharge and energy consumption.

Transmission Mains: High-frequency pressure transducers detect hydraulic surges (water hammers) and transient flows.

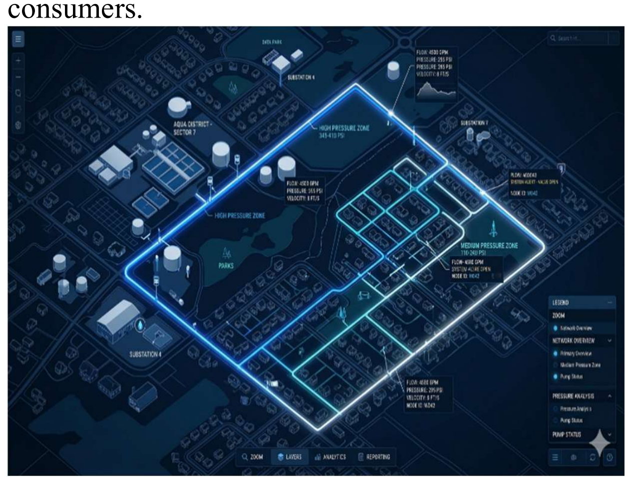
Storage Reservoirs and Distribution Nodes: Multi-parameter probes measure Turbidity, Electrical Conductivity (EC), pH, Temperature, and Residual Chlorine. These sensors transmit data via low-power wide-area network (LPWAN) protocols to a centralized cloud platform, ensuring continuous data flow even in remote geographical locations.

The "brain" of the methodology is a dynamic hydraulic model. The process began by digitizing the entire physical network using Geographic Information Systems (GIS), mapping every pipe’s material, diameter, age, and exact geodesic elevation. This data was then imported into EPANET. Unlike static models, this Digital Twin is "live"; it uses real-time flow and pressure data from the IoT layer to run continuous simulations, allowing the system to mirror the exact state of the physical

network at any given second.
The final layer utilizes Machine Learning algorithms developed in Python. These algorithms perform two critical functions:
Anomaly Detection: By comparing real-time data against the Digital Twin’s predicted values, the AI identifies discrepancies that signal a pipe burst or unauthorized water withdrawal.
Virtual Sensing: The model uses "Soft Sensors" to estimate water quality parameters at nodes where physical sensors are absent, using correlation matrices from existing data points.
The pilot implementation in Dedoplistskaro yielded transformative data, proving that digital integration significantly outperforms traditional management paradigms.
The most significant result was the collapse of the "detection-to-action" window. In traditional systems, a contamination event is often only discovered after consumer complaints or a 24-hour lab cycle. The automated system reduced this to 7–10 minutes. The discussion emphasizes that this window is short enough to trigger automated shut-off valves, effectively preventing contaminated water from reaching household taps.
By using the Digital Twin to identify "hidden" leaks—leaks that do not surface but result in massive water loss—the municipality achieved a 15-20% reduction in NRW. The system identifies these by detecting subtle pressure drops that do not align with programmed consumption patterns.
A key discussion point in the research is the "Optimal Sensor Placement" (OSP) algorithm. The study proved that total network visibility does not require a sensor on every pipe. By using AI to identify high-influence nodes, the research demonstrated that placing just 3 high-spec sensors could provide a 88% confidence level in monitoring the entire town's distribution safety, significantly lowering the barrier for entry for cash-strapped regional utilities.
The Smart Chlorination module eliminated the risk of over-chlorination (which creates harmful by-products) or under-chlorination (which risks bacterial growth). By analyzing turbidity and flow rates in real-time, the automated dosing pumps adjusted chemical input instantaneously. This resulted in a 12% reduction in chemical costs while maintaining a 100% compliance rate with health standards.
The results highlight that while technology is the driver, the methodology's success lies in reducing the "human factor." Automated alerts and AI-driven recommendations allow a small team of operators to manage a vast, complex regional network that previously required dozens of manual inspectors. This makes the model highly scalable for other regions of Georgia and similar developing infrastructures globally.

**3 Results**

The pilot implementation in Dedoplistskaro demonstrated that a digital-first approach transforms water management from reactive maintenance to a proactive, "self-healing" network. The key results are summarized below:
Minimized Crisis Response Time: Historically, Georgian water monitoring relied on manual sampling with a 24–48 hour laboratory delay. By integrating IoT and AI, the system now identifies quality anomalies (e.g., turbidity spikes or chlorine drops) in real-time. This reduces the response window to just 7–10 minutes, allowing automated valves to isolate contamination before it reaches consumers.




Mitigation of Non-Revenue Water (NRW): By synchronizing real-time pressure data with the EPANET digital twin, the model successfully identified "hidden" underground leaks. This precision allowed maintenance teams to pinpoint exact GPS coordinates for repairs without trial-and-error excavation, resulting in a documented 15–20% reduction in NRW.

Economic Viability via Strategic Sensing: To overcome high hardware costs, the study used an Optimal Sensor Placement (OSP) algorithm. Results proved that placing just three high-specification sensors at primary junctions provided an 88% visibility rate across all critical nodes, making "Smart Water" technology affordable for budget-constrained municipalities.

Intelligent Chemical Regulation: The introduction of an automated dosing feedback loop eliminated manual "set-and-forget" errors. By using AI to calculate exact chlorine needs based on real-time flow and turbidity, the system ensured 100% safety compliance while reducing chemical waste by 12–15%.

Operational Sustainability: The digital twin optimized energy consumption by simulating pumping schedules that align with low-tariff periods and efficient pressure zones. By preventing system over-pressurization, the methodology reduces energy waste and pipe bursts, effectively extending the infrastructure's lifespan.

In conclusion, the synergy of IoT and AI in Dedoplistskaro serves as a scalable blueprint for Georgia, proving that regional water systems can become resilient, sustainable, and safe with minimal human intervention.

## 4 Conclusion

The research concludes that the integration of Digital Twins, IoT, and Artificial Intelligence is not merely a technological upgrade but a fundamental necessity for the modernization of Georgia’s regional water infrastructure. The developed methodology provides a universal technological blueprint that successfully addresses the chronic inefficiencies of traditional water management systems. By transitioning from manual, reactive operations to an automated, data-driven framework, the study demonstrates a viable path toward ensuring the long-term sustainability and security of regional water supplies.

The practical evidence gathered from the Dedoplistskaro case study confirms that this methodology offers a dual advantage: operational resilience and economic feasibility. The significant reduction in response time—from days to minutes—proves that real-time monitoring can effectively safeguard public health against contamination risks. Furthermore, the documented 15-20% reduction in water losses (NRW) and the optimization of chemical and energy consumption highlight a clear economic incentive for regional utility providers. The research successfully refutes the notion that high-tech solutions are cost-prohibitive for smaller municipalities, showing instead that intelligent sensor placement and AI-driven analytics can achieve high system visibility with minimal hardware investment.


Looking ahead, this work serves as a foundational pillar for the realization of "Smart City" and "Smart Village" concepts across Georgia. The algorithms and digital frameworks established in this dissertation are scalable and adaptable to any geographic or topographic context. As Georgia moves toward greater European integration and higher environmental standards, the adoption of such innovative methodologies will be crucial. Ultimately, this research provides the tools to minimize human error, optimize natural and financial resources, and, most importantly, guarantee every citizen’s right to a continuous, safe, and high-quality water supply.

This methodology represents a significant scientific and practical contribution to the field of civil engineering and municipal management, bridging the gap between current infrastructural challenges and the digital future of urban utility networks.

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