



SCADA And IOT-Enabled Smart Water Metering: A Systematic Review of Resilient Supply Monitoring

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Abstract

This study has examined the contribution of SCADA and IoT-enabled smart water metering to resilient supply monitoring in digitally monitored water utility, cloud-enabled infrastructure, and enterprise-level smart water management cases. The main problem addressed in this research has been the continuing inability of many conventional and fragmented water monitoring systems to detect leakage, pressure instability, abnormal consumption, data delays, and operational faults in a timely and integrated manner. The purpose of the study has been to evaluate whether SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT integration significantly improve resilient supply monitoring. The study has followed a quantitative, cross-sectional, case-based research design and has collected data from 214 valid respondents, including water utility operations staff, SCADA operators and engineers, IoT and smart meter technicians, water distribution engineers, data analysts, monitoring specialists, and municipal water authority staff. Data have been analyzed through descriptive statistics, reliability analysis, correlation analysis, multiple regression modeling, hypothesis testing, leakage-pressure-abnormal consumption detection assessment, and a Resilience Readiness Index. The findings have shown strong agreement across the major constructs, with SCADA-IoT integration recording the highest mean score of 4.16, followed by resilient supply monitoring at 4.11, SCADA-based monitoring capability at 4.08, IoT-enabled smart metering capability at 4.02, real-time data quality at 3.96, and predictive analytics and anomaly detection at 3.89. Reliability has been confirmed through Cronbach's alpha values ranging from 0.82 to 0.90, with overall scale reliability of 0.92. Correlation results have shown significant positive relationships with resilient supply monitoring, led by SCADA-IoT integration at $r = 0.69$ and predictive analytics at $r = 0.63$. The regression model has been statistically significant, $F(5, 208) = 62.47$, $p < 0.001$, explaining 59.4% of the variance in resilient supply monitoring. SCADA-IoT integration has been the strongest predictor, $\beta = 0.31$, followed by predictive analytics, $\beta = 0.24$, SCADA capability, $\beta = 0.21$, IoT metering, $\beta = 0.18$, and real-time data quality, $\beta = 0.15$. The Resilience Readiness Index has scored 4.02 out of 5.00, confirming high readiness. The study implies that integrated SCADA-IoT systems can strengthen early warning, leakage visibility, pressure monitoring, abnormal-consumption detection, and data-driven response in resilient water supply operations.

Keywords

SCADA-IoT integration; smart water metering; resilient supply monitoring; predictive analytics; real-time data quality.

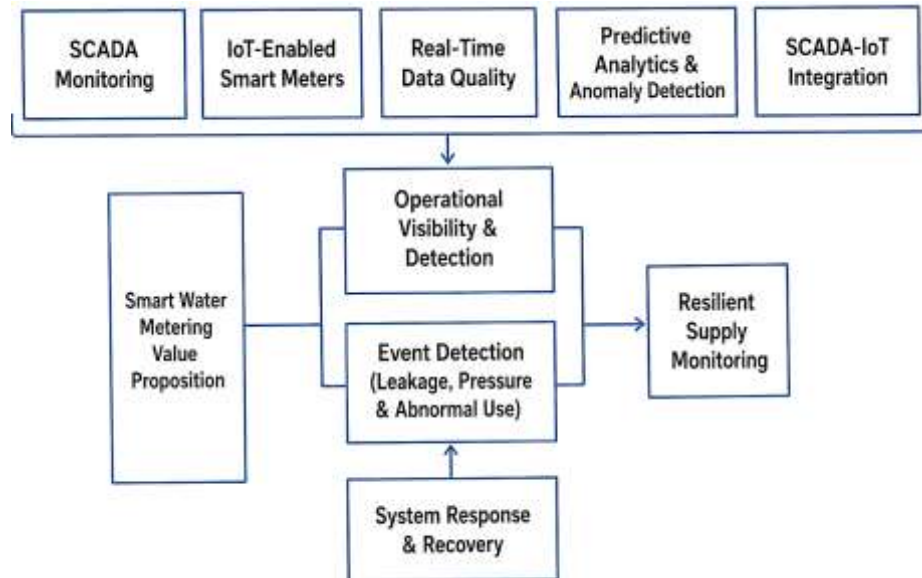
INTRODUCTION

Smart water metering refers to the use of digital metering devices, communication networks, data storage platforms, and analytical tools to measure, transmit, and interpret water consumption and distribution-system information with higher temporal and operational resolution than conventional manual meter reading. In water supply systems, this concept has been closely connected with automated meter reading, advanced metering infrastructure, sensor-based monitoring, household-level consumption profiling, pressure observation, and near-real-time event detection (Beal & Stewart, 2013). SCADA, or Supervisory Control and Data Acquisition, refers to a supervisory automation architecture that allows operators to observe, control, and respond to physical processes through sensors, programmable logic controllers, telemetry, alarms, human-machine interfaces, and centralized or distributed control logic. In water distribution systems, SCADA has been used to monitor pumps, reservoirs, tanks, valves, pressures, flows, alarms, and network operating states, while IoT has expanded the monitoring boundary toward distributed meters, low-power sensors, cloud platforms, wireless networks, and customer-side data streams (Robles et al., 2020). IoT has been defined as an interconnected system of physical objects with sensing, communication, and computational capability, enabling machine-to-machine and human-to-machine interaction across service environments (Atzori et al., 2010). In smart water systems, IoT-enabled metering has converted water-use information from occasional billing records into operational data that can support leakage identification, abnormal-consumption detection, demand characterization, and service-quality monitoring (Cominola et al., 2019). Resilient supply monitoring refers to the ability of a water supply system to observe disturbances, detect abnormal states, maintain service continuity, support rapid response, and recover operational performance after pressure, leakage, quality, cyber-physical, or demand-related disruptions. The resilience concept has been applied to infrastructure systems as a multidimensional property involving absorptive, adaptive, and restorative capacity, which makes it highly relevant to digitally monitored water networks (Hosseini et al., 2016). Within this definition-based foundation, SCADA and IoT-enabled smart water metering represent complementary technologies because SCADA supports supervisory visibility and control, while IoT-enabled meters strengthen distributed sensing, granular data collection, and consumption-level intelligence.

The international significance of SCADA and IoT-enabled smart water metering has been shaped by the growing pressure on water utilities to reduce water losses, maintain service reliability, improve operational efficiency, and protect essential infrastructure under increasingly complex urban and environmental conditions. Drinking water distribution systems have been treated as critical public-health and infrastructure systems because failures in distribution networks can affect access, water quality, pressure adequacy, public confidence, and service continuity (Lee & Schwab, 2005). Water utilities in both developed and developing economies have faced persistent challenges from non-revenue water, meter inaccuracy, illegal connections, pressure fluctuation, pipeline deterioration, and delayed fault recognition. Non-revenue water remains a global operational and financial problem, making measurement accuracy and leakage visibility central concerns for utility management (Liemberger & Wyatt, 2019). In this international context, smart water metering has been valued because it allows utilities to move from periodic and reactive measurement toward continuous and data-supported monitoring. Intelligent metering for urban water has been associated with improved utility knowledge of consumption, customer engagement, and sustainable water management (Beal & Stewart, 2013). Smart meters provide new opportunities for residential water demand modeling because high-resolution data can reveal usage behavior that conventional monthly meter readings cannot capture (Cominola et al., 2015). Smart metering also supports post-meter leakage identification, where metering-based communication and consumption feedback can improve water-loss management at the customer side (Britton et al., 2013). Internationally, smart water systems have also been associated with smart city infrastructure, because networked sensors and data platforms allow municipalities to connect water supply monitoring with broader urban resilience, environmental sustainability, and service management goals (Zanella et al., 2014). Smart meters, implementation models, system architectures, and loss management have been identified as major application categories in smart water management literature, showing that metering and monitoring are not isolated technical tools but central elements of modern water-service transformation (Ascensão et al.,

2023). Therefore, the international significance of this research lies in its focus on the combined role of SCADA, IoT-enabled meters, and resilience-oriented monitoring in strengthening water supply systems across diverse utility contexts.

Figure 1: SCADA-IoT-enabled smart water metering framework for operational visibility and resilient supply monitoring



The development of SCADA and IoT-enabled smart water metering has also been supported by advances in sensing, telemetry, communication, and cyber-physical infrastructure. Earlier work on wireless sensor networks for pipeline monitoring has shown that distributed sensor deployment can increase the spatial and temporal resolution of pipeline data, allowing utilities to identify bursts, leaks, blockages, and abnormal hydraulic behavior with greater operational detail (Shurovi & Hossain, 2022; Stoianov et al., 2007). SCADA systems have traditionally offered central supervisory control, yet their monitoring quality depends on sensor placement, telemetry reliability, alarm configuration, and operator interpretation. IoT-enabled smart metering has extended this architecture by placing measurement capability closer to end users, district-metered areas, and distribution zones, allowing consumption data to be collected at finer intervals and transmitted through wireless or internet-based networks. Connected devices can create new service ecosystems through sensing, identification, networking, and intelligent processing (Lee & Lee, 2015; Hossain, 2024). In water utility environments, these characteristics allow smart meters and sensors to function as data-generating assets rather than passive measurement devices. IoT has been presented as a framework for smart water supply management because it enables data integration from multiple sources, real-time contextual information, and service-quality improvement (Kanti, 2025; Robles et al., 2020). Smart meter data have also been used to uncover heterogeneous water-use behaviors, where high-resolution consumption patterns help identify differences among households and improve demand-side management strategies (Golam & Amir, 2023; Cominola et al., 2019). Digital feedback based on smart meter data has been linked with long-term water conservation, indicating that meter-enabled data can influence both utility-side monitoring and customer-side behavior (Amir & Chapal, 2022; Cominola et al., 2021). This technological foundation is especially relevant for a quantitative, cross-sectional, case-study-based study because respondents can evaluate observable system capabilities such as SCADA-based monitoring capability, IoT-enabled metering capability, data quality, predictive analytics, and SCADA-IoT integration. These constructs can be measured through a five-point Likert scale because professionals who operate, manage, or analyze smart water systems can assess whether the technologies improve visibility, detection, response, and continuity in actual water supply contexts. The resilience dimension of smart water metering has become important because water distribution

systems are vulnerable to hydraulic, mechanical, operational, environmental, and cyber-physical disruptions. Resilience in infrastructure research has been conceptualized as the ability of a system to withstand disturbance, absorb stress, recover performance, and adapt operationally after disruptive events (Amir, 2025; Hosseini et al., 2016). In water distribution systems, resilience has been linked with redundancy, robustness, network connectivity, pressure sufficiency, demand satisfaction, leakage control, and the ability to maintain water delivery during component failures or abnormal events (Amir, 2024; Shin et al., 2018). A network-theory approach has shown that structural connectivity and redundancy are important for system robustness in resilience-enhancing expansion strategies for water distribution systems (Sadia et al., 2022; Yazdani et al., 2011). Quantitative resilience measures for water infrastructure systems have been assessed through technical, hydraulic, performance-based, and recovery-related indicators (Shin et al., 2018; Zaman, 2024). These studies support the use of resilience theory as the theoretical foundation of this thesis because SCADA and IoT-enabled smart water metering can be interpreted as technological capabilities that strengthen system observation, disturbance detection, response coordination, and recovery support. Pressure monitoring and flow visibility are central because leakage, burst events, unauthorized consumption, and valve failure often appear first as abnormal hydraulic patterns. Pressure-driven demand and leakage simulation are important for understanding water distribution behavior under non-ideal operating conditions (Giustolisi et al., 2008). Leakage management in pipe networks depends on detection, assessment, control, and operational decision-making (Tohidul, 2023; Puust et al., 2010). Automated detection methods for pipe bursts and related events have demonstrated the relevance of near-real-time monitoring for event recognition at the district-metered-area level (Romano et al., 2014). In this way, resilient supply monitoring is not limited to physical network strength; it also depends on whether the utility can recognize changing conditions through continuous data streams and respond before minor disturbances become larger service interruptions.

Leakage, pressure instability, and abnormal consumption are among the most relevant operational problems for SCADA and IoT-enabled smart water metering because they directly connect measurement technology with water loss, service disruption, and customer-level supply reliability. Leakage in water distribution networks is technically difficult because losses may occur through background leakage, pipe bursts, service connection failures, meter-side losses, or unauthorized use. Traditional detection methods have often required field inspection, acoustic surveys, night-flow analysis, or customer complaints, while smart metering and sensor-based monitoring allow earlier recognition of consumption anomalies and hydraulic deviations. Smart metering has been connected with post-meter leakage identification and water loss management, while smart meter data have been shown to improve demand modeling because high-resolution records reveal patterns that aggregate billing data conceal (Britton et al., 2013). Leakage detection and localization methods for water piping networks require robust algorithms, data interpretation, and localization capability (Adedeji et al., 2017). Pipe bursts and unauthorized consumption can produce abnormal pressure or flow variations, making them suitable targets for automated event detection (Romano et al., 2014). Smart metering data can also support behavioral and operational segmentation because different consumers, districts, or facilities present different usage routines and abnormality thresholds (Cominola et al., 2019). These technical characteristics are central to the proposed result section on leakage, pressure, and abnormal-consumption detection performance because the research can measure whether professionals perceive SCADA-IoT systems as effective in identifying leakage-prone zones, pressure faults, abnormal consumption, and real-time warning conditions. The role of predictive analytics is also relevant because smart water monitoring produces time-series data that can be analyzed for anomalies, demand variation, and event probability. In such a context, data quality becomes a core construct because inaccurate, delayed, incomplete, or poorly integrated sensor data can weaken the value of both SCADA dashboards and IoT meter readings. Therefore, real-time data quality, predictive analytics, and anomaly detection are not secondary components of the study; they are essential mechanisms through which smart water metering becomes useful for resilient supply monitoring.

The integration of SCADA and IoT-enabled smart water metering also creates a cyber-physical layer in which physical water processes, digital communication systems, data analytics, and operational control are closely connected. Cyber-physical water systems have strengthened monitoring capacity, yet they

have also introduced reliability and security requirements because sensors, controllers, communication channels, databases, and dashboards must operate consistently for monitoring decisions to remain trustworthy. SCADA systems have received considerable attention in cyber-security research because they support critical infrastructure control and may be exposed to unauthorized access, false data injection, communication disruption, and manipulation of operational logic (Cherdantseva et al., 2016). Cyber-physical attacks on water distribution systems have shown how compromised sensors or controllers can affect hydraulic behavior and system operation (Taormina et al., 2017). Cyber-physical stress testing for water distribution networks has highlighted the importance of understanding how cyber actions interact with water quality and network operation (Nikolopoulos & Makropoulos, 2022). These studies are relevant to SCADA and IoT-enabled smart metering because resilient supply monitoring depends not only on collecting more data but also on ensuring that data are accurate, secure, timely, interpretable, and operationally connected. IoT architectures can improve monitoring coverage by connecting meters and sensors across a distribution system, but they also require interoperability, device reliability, power management, communication quality, and data governance. IoT-based water supply management can integrate multiple technologies and extract contextual information from different data sources (Robles et al., 2020). IoT-enabled smart city systems require communication, architecture, and service integration, which is relevant for water utilities that use smart meters as part of broader municipal digital infrastructure (Zanella et al., 2014). For this thesis, SCADA-IoT integration can therefore be treated as a major predictor of resilient supply monitoring because it reflects the degree to which supervisory control, distributed metering, real-time data quality, anomaly detection, and decision support operate as a unified monitoring system. This also supports the use of regression modeling because the study can statistically examine whether integrated capability explains resilience outcomes beyond individual SCADA or IoT capability alone.

A quantitative, cross-sectional, case-study-based study is suitable for this topic because SCADA and IoT-enabled smart water metering can be examined through measurable perceptions of system capability, operational visibility, detection performance, data quality, analytics readiness, and resilience monitoring. The systematic review component can organize the academic foundation by synthesizing research on smart water meters, SCADA, IoT architectures, leakage detection, cyber-physical security, and water infrastructure resilience, while the quantitative component can test whether the proposed relationships are supported in selected case contexts. The five-point Likert scale is appropriate because constructs such as SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, SCADA-IoT integration, and resilient supply monitoring are multidimensional and can be represented through multiple questionnaire items. Descriptive statistics can show the overall level of agreement on each construct, reliability analysis can assess the internal consistency of measurement items, correlation analysis can identify the strength and direction of relationships among the variables, and regression modeling can test the predictive contribution of each technology-related factor. Prior literature supports this variable logic because smart metering has been linked with demand modeling and conservation feedback (Cominola et al., 2021), IoT has been linked with connected service architectures and real-time water supply management (Robles et al., 2020), SCADA has been linked with critical infrastructure monitoring and cyber-physical risk assessment (Cherdantseva et al., 2016), and resilience studies have linked infrastructure performance with robustness, redundancy, recovery, and quantitative measurement (Shin et al., 2018). The study's special focus on leakage, pressure, abnormal-consumption detection, and a resilience readiness index also fits the specific nature of smart water monitoring because these sections translate technology adoption into operationally meaningful outcomes. Smart water management applications have commonly concentrated around smart meters, implementation models, architectures, and loss management, which aligns with the present focus on SCADA-IoT-enabled resilient supply monitoring (Ascensão et al., 2023). In this structure, the introduction establishes the definitions, global relevance, technological foundation, resilience basis, operational problem, cyber-physical concern, and quantitative research direction of the thesis without closing the discussion or shifting into recommendation-oriented claims.

Background of the study

Smart water metering has become an important part of modern water supply management because water utilities are increasingly required to monitor consumption, leakage, pressure, flow, service continuity, and system performance with greater accuracy and speed. Traditional water metering has mainly depended on manual reading or periodic billing-based measurement, which often fails to detect leakage, abnormal consumption, meter tampering, pressure instability, and supply interruption in real time. As a result, many water utilities face operational losses, delayed maintenance, customer dissatisfaction, and difficulty in managing limited water resources. SCADA and IoT-enabled smart water metering have introduced a more advanced monitoring approach by connecting supervisory control, remote sensing, automated meter reading, wireless communication, real-time dashboards, and data analytics into one digital water management environment. SCADA systems allow operators to supervise pumps, reservoirs, valves, tanks, pressure points, and flow conditions from a centralized platform, while IoT-enabled smart meters extend the monitoring capacity to customer-level and zone-level consumption points. This combination creates a stronger foundation for resilient supply monitoring because it helps water utilities observe the condition of the network continuously and respond to problems before they become severe service failures. In this research, resilient supply monitoring refers to the ability of a water supply system to detect abnormal events, maintain service continuity, support rapid operational response, and recover from disturbances through data-driven monitoring. The study has focused on SCADA and IoT-enabled smart water metering because these technologies can improve leakage detection, abnormal-consumption identification, real-time data quality, pressure monitoring, predictive analytics, and integrated decision-making. Since water supply systems are critical infrastructure, the use of digital monitoring is not only a technical improvement but also an operational necessity for efficient, reliable, and resilient water service delivery. Therefore, this study has examined how SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics, and SCADA-IoT integration contribute to resilient supply monitoring in selected case-based water utility contexts.

Problem statement

Water supply systems in many urban and semi-urban contexts still experience serious monitoring limitations because conventional metering and fragmented supervisory systems cannot always provide timely, accurate, and actionable information about network conditions. Leakage, pressure fluctuation, unauthorized use, meter tampering, abnormal consumption, pump failure, communication delays, and supply interruptions often remain unnoticed until they create visible service problems or financial losses. This creates a major operational challenge for water utilities because delayed detection increases non-revenue water, weakens customer service, raises maintenance costs, and reduces the reliability of supply monitoring. Although SCADA systems have been used for supervisory control in many water utilities, their effectiveness can be restricted when they are not integrated with distributed smart meters, IoT sensors, real-time analytics, and reliable data management platforms. Similarly, IoT-enabled smart meters can collect detailed consumption and event data, but their value remains limited when the data are not connected with utility-level operational control, anomaly detection, and resilience-based decision-making. The main problem is that many studies have discussed SCADA, IoT metering, leakage detection, smart water management, and infrastructure resilience separately, while fewer studies have quantitatively examined how these factors jointly influence resilient supply monitoring. This creates a gap in understanding whether SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics, and SCADA-IoT integration significantly improve water supply resilience. Another problem is that many technology-focused studies describe the benefits of smart water systems conceptually, but fewer studies test these benefits through measurable variables, professional responses, descriptive statistics, correlation analysis, and regression modeling. Therefore, this research addresses the need for a structured empirical model that can explain how integrated digital monitoring capabilities support resilient supply monitoring. The study also addresses the practical need to evaluate leakage, pressure, and abnormal-consumption detection performance because these operational issues directly determine the trustworthiness of smart water metering systems. By focusing on a quantitative, cross-sectional, case-study-based design, this research has aimed to provide measurable evidence on the contribution of

SCADA and IoT-enabled smart water metering to resilient supply monitoring.

Objectives of The Study

The main objective of this study has been to examine the role of SCADA and IoT-enabled smart water metering in improving resilient supply monitoring in selected water supply and utility monitoring contexts. More specifically, the study has aimed to evaluate how SCADA-based monitoring capability supports real-time visibility, supervisory control, alarm response, pressure monitoring, flow observation, and operational decision-making in water distribution systems. Another objective has been to assess how IoT-enabled smart metering capability contributes to customer-level consumption tracking, remote meter reading, distributed sensing, abnormal-consumption identification, and network-level monitoring. The study has also aimed to examine the role of real-time data quality because the effectiveness of smart water monitoring depends on whether the collected data are accurate, timely, complete, consistent, and useful for operational decisions. Another important objective has been to investigate how predictive analytics and anomaly detection support leakage identification, pressure fault recognition, meter tampering detection, demand visibility, and early warning generation. In addition, the study has aimed to test whether SCADA-IoT integration significantly predicts resilient supply monitoring by combining supervisory control, smart metering, sensor data, analytical capability, and dashboard-based decision support into one connected monitoring system. The study has also included a specific objective to evaluate leakage, pressure, and abnormal-consumption detection performance because these indicators directly represent the practical value of smart water monitoring technologies. Finally, the research has aimed to develop and interpret a resilience readiness index for SCADA-IoT smart water monitoring so that the overall readiness level of the case context can be understood in a measurable way. These objectives have guided the design of the questionnaire, the selection of variables, the development of hypotheses, and the choice of statistical techniques. Through descriptive statistics, reliability analysis, correlation analysis, and regression modeling, the study has attempted to determine whether digital monitoring capabilities can explain resilient water supply monitoring in a systematic and evidence-based manner.

Research hypotheses

The research hypotheses of this study have been developed to test the expected relationships between SCADA and IoT-enabled smart water metering capabilities and resilient supply monitoring. Since the study follows a quantitative, cross-sectional, case-study-based design, the hypotheses are structured around measurable variables that can be tested through correlation analysis and regression modeling. The first hypothesis states that SCADA-based monitoring capability has a significant positive effect on resilient supply monitoring. This hypothesis is based on the idea that supervisory control, alarm systems, real-time operational dashboards, pump monitoring, pressure tracking, valve control, and flow visibility can improve the ability of water utilities to identify disruptions and maintain service continuity. The second hypothesis states that IoT-enabled smart metering capability has a significant positive effect on resilient supply monitoring. This hypothesis assumes that smart meters, sensors, remote reading, customer-level data, wireless communication, and distributed monitoring improve the utility's ability to understand consumption behavior and detect abnormal usage. The third hypothesis states that real-time data quality has a significant positive effect on resilient supply monitoring because inaccurate, incomplete, delayed, or inconsistent data can reduce the usefulness of both SCADA and IoT-enabled monitoring systems. The fourth hypothesis states that predictive analytics and anomaly detection have a significant positive effect on resilient supply monitoring. This hypothesis focuses on the ability of analytics tools to identify leakage, pressure irregularity, abnormal consumption, demand variation, and possible supply faults before they develop into wider service problems. The fifth hypothesis states that SCADA-IoT integration has a significant positive effect on resilient supply monitoring because integrated systems can combine centralized supervisory control with distributed metering and sensor-based intelligence. Therefore, the hypotheses of this study are: H1: SCADA-based monitoring capability has a significant positive effect on resilient supply monitoring; H2: IoT-enabled smart metering capability has a significant positive effect on resilient supply monitoring; H3: real-time data quality has a significant positive effect on resilient supply monitoring; H4: predictive analytics and anomaly detection have a significant positive effect on resilient supply monitoring; and H5: SCADA-IoT integration has a significant positive effect on resilient supply monitoring.

Significance of the research

- i. **Academic significance:** This research is significant because it contributes to the academic understanding of smart water monitoring by connecting SCADA, IoT-enabled metering, real-time data quality, predictive analytics, and resilient supply monitoring within one quantitative model. Many studies discuss these areas separately, but this study brings them together in a structured framework that can be tested through descriptive statistics, correlation analysis, and regression modeling. This strengthens the academic value of the research by showing how digital monitoring capabilities can be measured as predictors of water supply resilience.
- ii. **Methodological significance:** The study is significant because it uses a quantitative, cross-sectional, case-study-based design to examine a topic that is often discussed from a technical or conceptual perspective. By using a five-point Likert scale, reliability analysis, correlation analysis, and regression modeling, the study provides a measurable approach to evaluating smart water monitoring capability. The addition of leakage, pressure, and abnormal-consumption detection performance also makes the result structure more specific to water utility operations.
- iii. **Practical significance for water utilities:** This research is useful for water utilities because it identifies the specific monitoring capabilities that can improve service reliability and operational response. The findings can help utility managers understand whether SCADA systems, IoT-enabled meters, data quality, predictive analytics, and system integration are supporting resilient supply monitoring. This can help utilities improve leakage response, pressure monitoring, abnormal-consumption detection, and operational decision-making.
- iv. **Significance for infrastructure resilience:** The research is significant for infrastructure resilience because water supply systems are essential public-service systems. A resilient monitoring system can help identify problems early, reduce service disruption, support faster response, and improve recovery from operational disturbances. By focusing on resilience readiness, the study provides a practical way to understand whether a smart water monitoring system is prepared to support reliable supply management.
- v. **Significance for policy and planning:** The study is also significant for municipal authorities, smart city planners, and infrastructure decision-makers. It can support evidence-based planning for digital water infrastructure investment, smart meter deployment, SCADA modernization, IoT integration, and data analytics development. The research can help decision-makers understand that smart water metering is not only a billing technology but also a resilience-oriented monitoring tool.

LITERATURE REVIEW

The literature on SCADA and IoT-enabled smart water metering has developed across several connected research areas, including smart water metering, supervisory control, IoT-based sensing, water distribution monitoring, leakage detection, data analytics, and infrastructure resilience. Smart water metering literature has mainly focused on the transition from manual or periodic meter reading to digital, automated, and high-resolution consumption monitoring. This area explains how smart meters can improve customer-level visibility, demand analysis, abnormal usage detection, and utility-side decision-making. SCADA-related literature has focused on supervisory control and operational monitoring in water distribution systems, especially in relation to pumps, valves, reservoirs, pressure points, flow conditions, alarms, and centralized control rooms. IoT-based water monitoring literature has expanded this discussion by showing how sensors, wireless networks, cloud platforms, edge devices, and distributed smart meters can create more detailed and flexible monitoring environments. Another important stream of literature has examined leakage detection, pressure monitoring, burst identification, and abnormal-consumption analysis, which are highly relevant to water loss control and service continuity. At the same time, data quality and predictive analytics literature has shown that smart water monitoring depends not only on the presence of digital devices but also on the accuracy, timeliness, completeness, and interpretability of the data produced by those devices. The resilience literature adds another important foundation by explaining how infrastructure systems can prepare for, absorb, respond to, and recover from disturbances. In the context of this study, resilience theory provides a suitable theoretical foundation because SCADA and IoT-enabled smart metering can be understood as technological capabilities that strengthen visibility, early warning, adaptive response, and recovery support in water supply systems. The conceptual literature also supports the

development of a model in which SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT integration are treated as independent variables that influence resilient supply monitoring. Therefore, this literature review will synthesize the most relevant studies to explain the technological, operational, analytical, and resilience-based foundations of smart water monitoring.

Smart water metering and digital transformation in water utilities

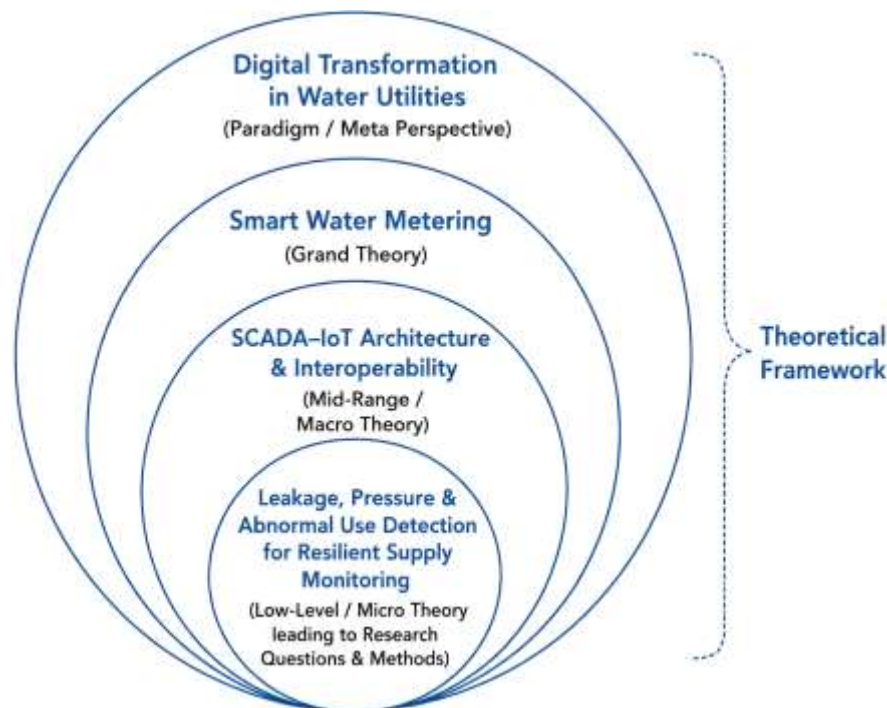
Smart water metering has become one of the most important entry points for digital transformation in water utilities because it changes water measurement from a slow billing activity into a continuous information process that supports monitoring, planning, and operational control. Traditional water metering usually depends on manual reading, delayed billing cycles, and limited visibility of customer-side consumption, while smart water meters can collect and transmit water-use data at shorter intervals through wireless communication, automated reading, and digital platforms. This transformation is highly relevant for water utilities because water distribution systems require timely information about consumption behavior, meter performance, pressure variation, leakage indicators, and abnormal usage. Digital transformation in the water sector is not only a matter of installing devices; it also involves changes in data governance, utility culture, information technology, operational technology, decision routines, and customer-service practices. A global survey of water utilities has shown that digital transformation is already affecting multiple parts of the urban water cycle, including distribution networks, customer demand management, data warehouses, and operating systems (Daniel et al., 2023; Ali et al., 2025). Within this transformation, smart water metering works as a practical data-generation layer because meters provide repeated observations of consumption at household, commercial, institutional, or district levels. These observations can help utilities move from reactive maintenance to evidence-based monitoring because irregular consumption patterns, continuous night flow, and sudden changes in meter readings can indicate leakage or unauthorized use. Smart water metering also supports the broader aim of resilient supply monitoring because a utility cannot respond quickly to hidden operational problems unless it has reliable information from the network and users. Therefore, smart water metering should be understood as a digital utility capability that links measurement, communication, analytics, and operational response within the water supply system.

The literature also shows that smart water metering depends on the strength of the technical architecture behind the meter, especially communication protocols, gateways, middleware, and interoperability arrangements. A major weakness of many smart metering systems is that hardware vendors often use proprietary technologies, which can create vendor lock-in, increase implementation costs, reduce data control, and make future system integration more difficult for water utilities. This issue is directly relevant to SCADA and IoT-enabled smart water metering because SCADA platforms, IoT sensors, meter data management systems, and utility dashboards must exchange data in a consistent and usable format. Wireless middleware has therefore become important because it allows smart water meters using different communication technologies to be connected through a more flexible and interoperable architecture (Alvisi et al., 2019; Hossan, 2025). In practical utility settings, this means that smart metering is not simply a matter of replacing analog meters with digital meters; it also requires an integrated communication environment that can support data acquisition, storage, transmission, validation, and operational interpretation. IoT-based smart metering architecture has also been strengthened by low-power wide-area technologies such as LoRaWAN, which can support long-range communication, low energy consumption, and scalable data transmission for water management applications. Pilot evidence has shown that smart metering systems can be designed through modular IoT platforms using next-generation sensors, LoRaWAN communication, and gateway-based architecture for water consumption measurement and crisis detection (Arif Uz et al., 2025; Slaný et al., 2020). This type of architecture is important for resilient supply monitoring because smart meters must remain functional across wide service areas, including locations where communication reliability, power availability, and device maintenance are operational concerns. When smart meters are connected to SCADA or utility monitoring systems, their value increases because the data can support both customer-side consumption analysis and distribution-side operational supervision. Therefore, the technical literature indicates that interoperability, communication

reliability, and modular IoT design are essential foundations for successful smart water metering implementation.

Smart water metering also contributes to digital transformation by improving leakage detection, real-time consumption visualization, and abnormal-use identification, which are directly connected with the present study's focus on resilient supply monitoring. Water utilities often lose significant quantities of treated water because hidden leaks, internal household leakage, pipe bursts, and irregular consumption are not detected in time. Smart metering can reduce this monitoring gap because continuous or high-frequency meter data can reveal patterns that are difficult to identify through monthly readings. Large-scale experimentation with automated meter reading has shown that intelligent water meter technology can support clear consumption-pattern monitoring and rapid leakage detection in a large campus environment (Farah & Shahrou, 2018; Zaman, 2024).

Figure 2: Multi-level theoretical framework for smart water metering and resilient water utility transformation

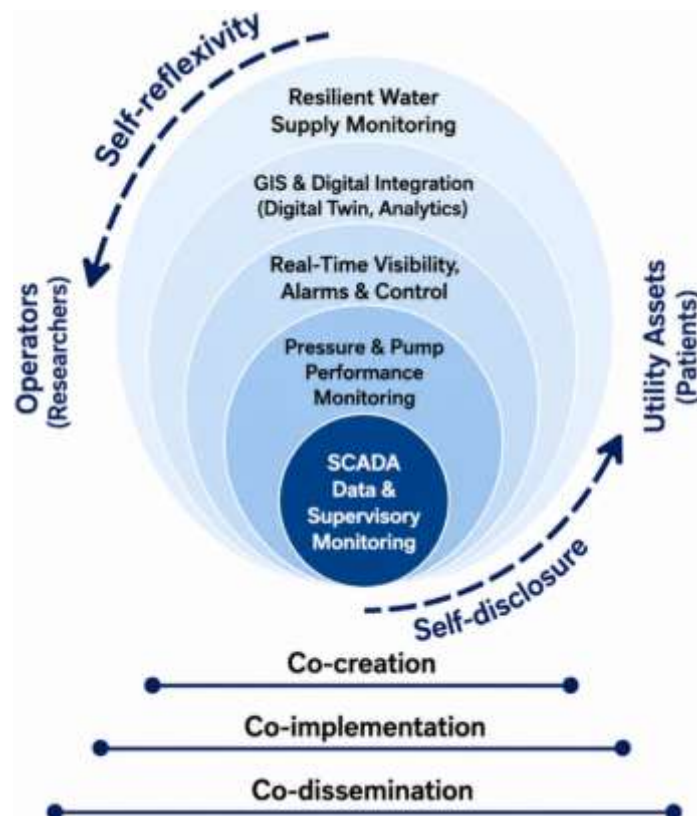


IoT and cloud-based smart water consumption systems have also demonstrated how smart meters, local gateways, cloud servers, web interfaces, and rule-based algorithms can be combined to visualize consumption in real time and detect possible leaks across different consumption scenarios (Fuentes & Mauricio, 2020; Ali et al., 2024). These findings are highly relevant for the proposed thesis because resilient supply monitoring depends on the ability to identify problems early, distinguish normal from abnormal consumption, and provide operators with actionable data. In a SCADA-IoT-enabled water supply context, smart meters can function as distributed data points that complement supervisory monitoring from pumps, tanks, valves, and pressure sensors. This supports a more complete monitoring structure because utility operators can observe both system-level hydraulic conditions and user-level consumption behavior. Smart metering also strengthens the evidence base for descriptive statistics, correlation analysis, and regression modeling in the present study because professionals can assess whether smart meter data improve visibility, leakage response, data quality, and operational confidence. As a result, the literature positions smart water metering as a practical and measurable component of digital transformation that connects utility modernization with resilient, data-driven supply monitoring.

SCADA systems for supervisory control and water supply monitoring

SCADA systems have become a central component of supervisory control and operational monitoring in water supply systems because they allow utilities to observe, control, and respond to distributed hydraulic assets from a coordinated digital environment. In water distribution and treatment contexts, SCADA normally connects field instruments, sensors, programmable logic controllers, remote terminal units, communication networks, human-machine interfaces, alarm systems, and central control rooms. Through this architecture, operators can monitor pumps, motors, valves, reservoirs, treatment units, pressure points, flow meters, and storage levels in near real time. The importance of SCADA in water supply monitoring can be understood from the operational nature of water utilities, where assets are geographically dispersed and many failures occur outside direct human observation. A supervisory platform allows operators to receive continuous signals from the network and compare observed conditions with expected performance. This is especially important for water supply systems because pressure imbalance, pump inefficiency, unexpected tank-level changes, flow irregularities, and equipment malfunction can affect service continuity. SCADA also supports operational decision-making because it transforms field measurements into dashboard information, alarms, logs, and control commands. In digitally managed utilities, SCADA is not only a control-room technology; it also functions as a bridge between field operations and broader information systems. Urban water infrastructure condition assessment depends on reliable data from different information systems, and SCADA has been identified as one of the important systems used by utilities for control, operation, management, and planning activities (Carriço & Ferreira, 2021; Hossan, 2024). This makes SCADA highly relevant to the present study because resilient supply monitoring depends on the availability of accurate operational information. When SCADA data are properly captured and interpreted, utilities can improve awareness of hydraulic conditions, support maintenance planning, and reduce delayed responses to network disturbances. Therefore, SCADA-based monitoring capability represents one of the core independent variables of this research because it reflects the extent to which supervisory control strengthens visibility, response, and reliability in smart water supply monitoring.

Figure 3: SCADA-based supervisory control framework for digital water supply monitoring



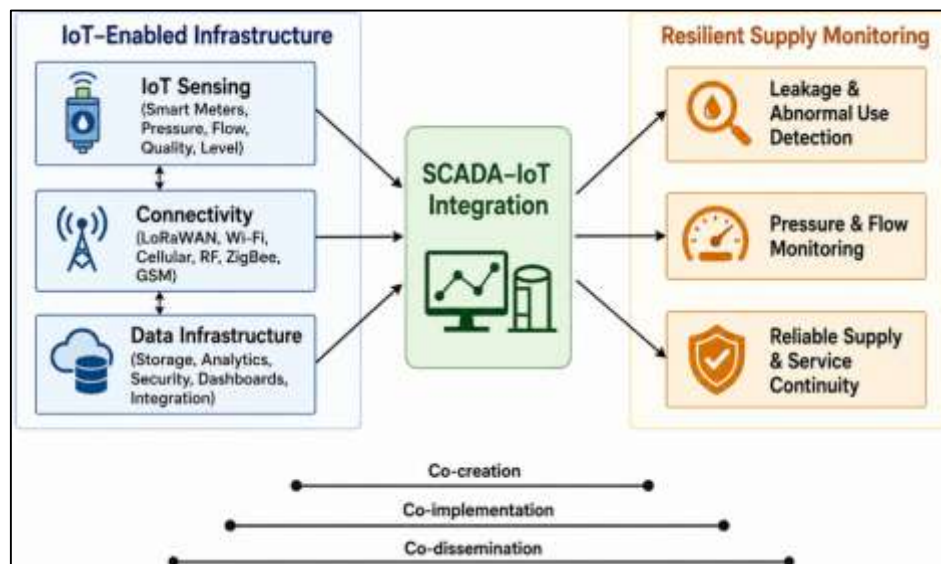
SCADA systems are also important because they provide the measurement and control foundation for pressure monitoring, pump-performance observation, energy management, and operational optimization. Pressure is one of the most critical variables in water distribution systems because it influences leakage rate, customer service quality, pipe stress, burst risk, and the reliability of supply under changing demand conditions. Pressure-monitoring research has shown that low-cost and scalable pressure monitoring tools can be compared with SCADA-based monitoring systems to strengthen the knowledge of pressure behavior in water distribution networks (Bruno et al., 2021; Risha & Khalid, 2023). This means that SCADA can operate as a benchmark monitoring environment while new IoT-based or low-cost sensor systems expand the number of monitoring points across the network. Pumping systems are another key area of SCADA application because pumps consume energy, regulate flows, maintain reservoir levels, and influence pressure distribution. Pump degradation can reduce system performance, raise maintenance requirements, and affect water supply reliability. Online monitoring data accumulated through SCADA have been used to analyze pump performance and support practical maintenance-oriented evaluation in water treatment plants (Hossan & Adar, 2023; Namba et al., 2023). This shows that SCADA data can move beyond simple observation and support performance diagnosis when the collected signals are processed and interpreted properly. In addition, SCADA can be integrated with spatial and geographic information systems to improve operational visibility in complex water infrastructure. GIS-SCADA integration has been used to improve the operational efficiency of water desalination systems by linking supervisory control data with spatially organized infrastructure information (Kamal & Ali, 2023; Badrul & Mominul, 2023). Such integration is relevant to water supply monitoring because utilities need to understand not only what is happening in the system but also where it is happening. Therefore, the value of SCADA in supervisory control is strongly connected with its ability to provide continuous operational data, support pressure and pump monitoring, integrate with location-based systems, and assist operators in making informed decisions during normal and abnormal operating conditions.

The role of SCADA in modern water supply monitoring has expanded further as utilities combine supervisory control with digital models, real-time analytics, and advanced decision-support platforms. Earlier SCADA systems were mainly used for direct monitoring and control, while contemporary water utilities increasingly use SCADA data as an input for simulation, digital twins, asset management, cyber-physical monitoring, and resilience-oriented decision-making. Digital-twin development in drinking water distribution networks has shown that real-time sensor data, hydraulic models, GIS data, meter information, and SCADA connections can be combined to support operational analysis, leak pre-location, energy efficiency, water quality prediction, and emergency response (Conejos et al., 2020; Tohidul, 2023). This is directly connected with the present research because SCADA and IoT-enabled smart water metering must operate together if utilities want a more complete picture of supply conditions. SCADA gives operators central supervisory visibility, while IoT-enabled smart meters add distributed consumption and event information from customer or zone-level points. When these data streams are integrated, the water utility can connect system-level control with consumption-level monitoring. This integration is important for resilient supply monitoring because disturbances may appear in different forms, such as pressure drops, abnormal flow, pump inefficiency, sudden consumption changes, valve malfunction, or delayed tank recovery. SCADA also supports accountability because it stores historical records that can be used to reconstruct events, examine trends, compare operating periods, and identify recurring weaknesses in the supply network. For a quantitative cross-sectional study, SCADA-based monitoring capability can therefore be measured through items related to real-time visibility, alarm usefulness, pump and valve supervision, pressure and flow monitoring, operator response, and integration with other digital systems. These measurement areas allow the study to test whether stronger SCADA capability is associated with resilient supply monitoring. In this way, SCADA literature supports the hypothesis that supervisory control systems contribute to resilience by improving observation, control, diagnosis, and response across water supply operations.

IoT-enabled sensing and smart meter data infrastructure

IoT-enabled sensing has become a major foundation of smart water metering because it allows water utilities to collect, transmit, and interpret data from distributed points across a water supply system. In conventional water infrastructure, many monitoring activities depend on manual inspection, delayed meter reading, or isolated supervisory systems, which can limit visibility of consumption, leakage, pressure, flow, and quality conditions. IoT-enabled sensing changes this condition by connecting smart meters, pressure sensors, flow sensors, level sensors, water quality sensors, gateways, communication modules, and cloud-based platforms into a more continuous data environment. This is important for resilient supply monitoring because the utility can only detect abnormal events when the system produces timely and reliable signals from different parts of the network. IoT-enabled water distribution literature has shown that water distribution systems require coordinated attention to accessibility, quality, quantity, and reliability, and that IoT technologies can support monitoring and control across different stages of the distribution process (Sadia et al., 2022; Velayudhan et al., 2022). In a smart water metering context, sensing infrastructure works as the first layer of digital transformation because all analytics, alarms, dashboards, and operational decisions depend on the quality of data produced by sensors and meters. Smart meters can record customer-level consumption, pressure sensors can indicate hydraulic instability, flow sensors can identify unusual movement of water, and quality sensors can support the monitoring of parameters such as turbidity, pH, temperature, conductivity, or residual chlorine. A systematic review of IoT-based water monitoring systems has also shown that real-time data acquisition, sensor selection, data-gathering systems, and reliable datasets are central issues in water monitoring applications (Kanti & Rony, 2022; Zulkifli et al., 2022). Therefore, IoT-enabled sensing is not only a technical addition to water utilities; it is the measurement base that allows SCADA and smart metering systems to identify hidden changes in the water supply environment.

Figure 4: IoT-enabled smart meter data infrastructure framework for resilient water supply monitoring



Connectivity is the second major component of IoT-enabled smart water metering because sensor data must move from field devices to gateways, databases, dashboards, and decision-support tools in a dependable manner. A smart meter or sensor has limited value if it can measure data but cannot transmit it regularly, securely, and accurately to the utility platform. For this reason, IoT-based water monitoring systems normally depend on wireless communication technologies such as Wi-Fi, GSM, ZigBee, Bluetooth, LoRaWAN, cellular networks, radio-frequency communication, or hybrid communication designs. The selection of communication technology depends on network coverage, power availability, data frequency, cost, terrain, pipe-network layout, and the number of devices installed across the service area. In water distribution systems, this issue is especially important because

meters and sensors are often placed in buried, remote, or geographically dispersed locations where communication failure can reduce the value of the monitoring system. Research on self-sufficient IoT applications for water distribution has shown that pressure and flow monitoring requires low-cost and low-energy communication solutions because large metropolitan areas create challenges for wide-area sensor deployment (De Oliveira et al., 2023; Muhammad Mohiul & Mohammad Badrul, 2022). Wireless sensor network research has also shown that decentralized smart monitoring can improve current centralized and manual methods by making water monitoring more adaptable to dynamic and heterogeneous urban water infrastructure (Hasan & Uddin, 2022; Martínez et al., 2020). These findings are relevant to SCADA and IoT-enabled smart water metering because the study focuses on integrated monitoring rather than isolated device installation. Connectivity allows IoT meters and sensors to become part of a wider operational system where SCADA operators, utility engineers, and data analysts can receive information from multiple points and compare it with system-level operating conditions. When communication networks are reliable, IoT-enabled meters can support abnormal-consumption detection, pressure-event identification, leakage alerts, and real-time service monitoring. Therefore, connectivity represents the communication backbone of smart meter data infrastructure and directly influences whether IoT sensing can support resilient supply monitoring.

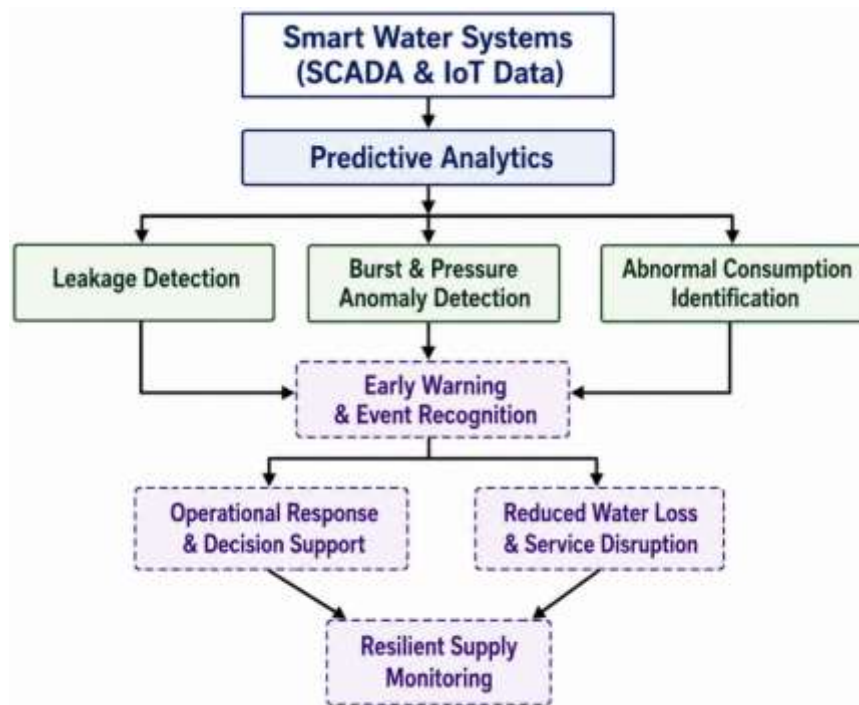
Smart meter data infrastructure is the third important part of IoT-enabled water monitoring because collected data must be stored, cleaned, validated, analyzed, visualized, and converted into useful operational information. A utility that installs smart meters without a strong data infrastructure may face large volumes of unreadable, incomplete, delayed, duplicated, or poorly integrated data. Smart meter data infrastructure includes meter data management systems, cloud storage, databases, application programming interfaces, cybersecurity controls, data dashboards, analytics engines, alert systems, and integration layers that connect IoT data with SCADA or other utility platforms. In water supply monitoring, this infrastructure must support both high-frequency operational data and longer-term historical records so that utilities can analyze daily consumption, night flow, seasonal patterns, event recurrence, leakage duration, pressure variation, and customer-side irregularities. IoT-based smart water quality monitoring literature has identified real-time feedback, communication coverage, energy management, data security, and domestic water monitoring as major challenges and requirements in connected water systems (Jan et al., 2021). This shows that smart water monitoring is not only about deploying sensors; it also requires systems that can maintain data quality and protect the reliability of the information chain. For the present thesis, smart meter data infrastructure is directly related to the variables of real-time data quality, predictive analytics, anomaly detection, and SCADA-IoT integration. If data infrastructure is strong, smart meters and sensors can produce information that helps detect leakage, pressure faults, abnormal consumption, and supply irregularities. If data infrastructure is weak, the same devices may produce large amounts of data without improving operational response. Therefore, the literature supports the view that IoT-enabled sensing, connectivity, and smart meter data infrastructure should be examined as interdependent components. Together, these components explain how smart water metering moves from device-level measurement to resilient supply monitoring, where distributed data streams are connected with supervisory control, analytics, and utility decision-making.

Predictive analytics and anomaly identification in smart water systems

Predictive analytics has become a major component of smart water systems because it allows water utilities to move from simple data recording toward early recognition of leakage, burst events, pressure irregularities, and abnormal consumption. In SCADA and IoT-enabled smart water metering, sensors and smart meters continuously produce pressure, flow, consumption, and event-related data that can be used to identify changes in system behavior. Leakage detection is especially important because water losses may remain hidden underground, inside customer premises, or within district-metered areas for a long period when utilities depend only on manual inspection or customer complaints. Predictive analytics uses statistical models, machine learning algorithms, signal-processing techniques, and classification methods to detect patterns that differ from normal hydraulic or consumption behavior. Real-time burst detection has been strengthened through disturbance extraction and isolation forest methods, where pressure measurements are analyzed to identify subtle burst signals from noisy background data (MABdur & Iftekhar, 2021; Xu et al., 2020). This kind of analytics is directly relevant

to resilient supply monitoring because a water utility must recognize early disturbance signals before they develop into wider service disruption. Leakage detection based on high-frequency pressure data also shows that single-feature detection may be limited by background pressure fluctuation, while multi-feature extraction can improve detection performance by combining instantaneous and trend characteristics of pressure changes (Wu et al., 2023). These findings indicate that smart water analytics depends not only on the presence of sensors but also on the ability to extract meaningful indicators from complex and changing network data. Therefore, predictive analytics provides the analytical layer that connects SCADA and IoT-enabled smart water metering with practical leakage detection, anomaly recognition, and early warning.

Figure 5: Predictive analytics framework for smart water leakage and anomaly detection



Machine learning has become increasingly important in leakage and anomaly detection because water distribution systems generate complex time-series data that may contain irregular patterns, seasonal demand changes, sensor noise, and hidden failures. In a district-metered area, leakage may appear as a slow deviation from normal flow or pressure behavior rather than as a sudden and obvious event. For this reason, anomaly detection methods must be able to recognize small deviations, compare them with historical patterns, and reduce false alarms. Machine learning-based emergent leak detection has shown that hourly inflow, loss, consumption, and pressure data can be used to identify leaks and anomalies within district-metered areas, including cases where leak signals are small at the beginning (Glomb et al., 2023). This is important for smart water metering because IoT meters and SCADA systems can produce the continuous input needed for such models. However, centralized analytics may become difficult when a system contains many sensors, wide service areas, or limited communication resources. Distributed computing approaches have addressed this issue by allowing local sensor nodes to collaborate with nearby nodes instead of sending all information to a central platform. A distributed Kalman filter approach for wireless-sensor-network-based water pipeline monitoring has shown that leakage detection can be supported through local computation, distributed data fusion, and lower communication dependency (Nkemeni et al., 2020). This type of method is relevant for resilient supply monitoring because it supports faster local detection and reduces reliance on a single central processing point. In SCADA-IoT-enabled systems, such distributed intelligence can complement central supervisory control by making field-level sensing more responsive. Therefore,

machine learning and distributed analytics strengthen the ability of smart water systems to detect operational anomalies under noisy, incomplete, or spatially dispersed monitoring conditions. Anomaly identification in smart water systems also requires methods that can interpret spatial relationships across a distribution network because leakage and burst events affect nearby pressure points, flow directions, and demand zones differently. Smart water metering provides customer-side and zone-level consumption information, while SCADA and pressure sensors provide operational information about pumps, valves, tanks, reservoirs, and distribution conditions. When these data sources are combined, predictive analytics can identify where abnormal behavior is likely occurring and whether it is related to leakage, burst events, unauthorized use, sensor malfunction, or operational disturbance. Deep learning has been applied to burst detection in smart water distribution systems by using spatially distributed pressure-response information and advanced metering infrastructure demand data, showing that convolutional neural networks can learn complex pressure patterns associated with burst events (Jun & Lansey, 2023). This is relevant to the current study because leakage, pressure, and abnormal-consumption detection performance has been proposed as a unique result section. Predictive analytics gives measurable support to that section by explaining how smart monitoring data can be transformed into detection outputs. In a quantitative survey-based thesis, professionals can evaluate whether predictive analytics improves leakage identification, abnormal consumption recognition, pressure-fault detection, and response confidence. These perceptions can then be measured through Likert-scale items and tested through correlation and regression analysis. The literature shows that leakage detection and anomaly identification depend on several connected elements: reliable sensor data, high-frequency pressure or flow observations, machine learning capability, distributed computation, and integration between SCADA and IoT-enabled metering systems. Therefore, predictive analytics represents a key mechanism through which smart water metering becomes useful for resilient supply monitoring, because it converts raw digital measurements into operational warnings, diagnostic signals, and decision-support information.

Resilience theory in smart water supply monitoring

Resilience theory has provided the theoretical foundation for this study because smart water supply monitoring is mainly concerned with how a water system observes disturbances, maintains functionality, responds to abnormal events, and restores reliable service after disruption. In infrastructure studies, resilience has been treated as a system property that goes beyond ordinary efficiency because an efficient system can still fail when it has weak detection, low redundancy, poor recovery capability, or limited adaptive capacity. In the context of SCADA and IoT-enabled smart water metering, resilience theory is especially suitable because water utilities operate as cyber-physical service systems where pumps, pipes, valves, reservoirs, meters, sensors, communication networks, dashboards, and operators must work together to maintain supply continuity. Resilience management emphasizes preparation, absorption, recovery, and adaptation in complex systems, which makes it relevant for water utilities that face leakage, pressure instability, sensor failure, abnormal consumption, communication disruption, pump malfunction, and cyber-physical disturbance (Linkov et al., 2014). The theory also supports the idea that infrastructure resilience must be measured through system performance rather than through technology presence alone. In other words, the installation of SCADA platforms and smart meters does not automatically create resilience unless these technologies improve detection, response, continuity, and recovery. Water management research has also emphasized that reliable, resilient, and sustainable service provision requires attention to both known operational stresses and uncertain external threats, which makes resilience theory suitable for understanding how smart monitoring helps utilities maintain safe and dependable water services (Butler et al., 2017). Therefore, this theoretical framework has positioned SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT integration as resilience-building capabilities. These capabilities support resilient supply monitoring by strengthening visibility, alert generation, operational coordination, and system response.

A key advantage of resilience theory is that it can be translated into measurable constructs for a quantitative, cross-sectional, case-study-based study. Resilience is often represented as the ability of a system to preserve or recover functionality across time after a disruptive event. Quantitative resilience

studies have proposed performance-based measures in which the functionality of a system is observed before, during, and after disruption (Henry & Ramirez-Marquez, 2012). For this thesis, the most applicable equation is a Resilience Readiness Index because the study uses Likert-scale survey data rather than direct hydraulic time-series data from the utility network. The proposed theoretical equation for the whole study is presented as follows:

$$RRI = \frac{SMC + ISMC + RTDQ + PAAD + SII}{5}$$

In this equation, *RRI* refers to the Resilience Readiness Index, *SMC* refers to SCADA-based monitoring capability, *ISMC* refers to IoT-enabled smart metering capability, *RTDQ* refers to real-time data quality, *PAAD* refers to predictive analytics and anomaly detection, and *SII* refers to SCADA-IoT integration. The theoretical structure of the model can also be expressed as:

$$RRI = f(SMC, ISMC, RTDQ, PAAD, SII)$$

This means that resilience readiness is treated as a function of SCADA monitoring strength, IoT-enabled metering capability, data quality, predictive analytics, and system integration. The interpretation level of the index can be presented as:

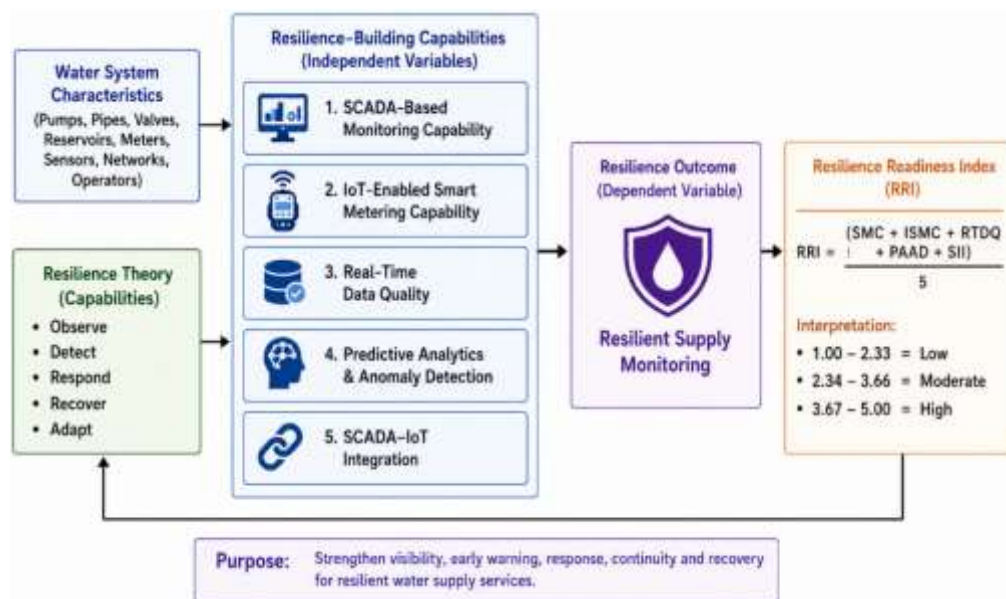
$1.00 \leq RRI \leq 2.33$ = Low resilience readiness

$2.34 \leq RRI \leq 3.66$ = Moderate resilience readiness

$3.67 \leq RRI \leq 5.00$ = High resilience readiness

This formula is appropriate because it converts the five major explanatory constructs of the study into one interpretable readiness score. The equation follows the logic of operational resilience because it focuses on the combined capacity of the system to observe, detect, analyze, integrate, and respond. Operational resilience research has shown that resilience can be assessed through critical functionality and performance-based measurement across disruptive conditions (Ganin et al., 2016). Therefore, the proposed equation gives this thesis a clear theoretical and statistical bridge between resilience theory and the Likert-scale measurement model.

Figure 6: Resilience theory framework for resilient water supply monitoring using SCADA and IoT technologies



Resilience theory also helps explain why SCADA and IoT-enabled smart water metering must be studied as an integrated system rather than as separate technologies. Civil infrastructure resilience is closely connected with the ability of a system to continue providing service under stress, reduce the

consequences of failure, and restore acceptable performance after disturbance (Bocchini et al., 2014). In water supply monitoring, this means that resilience depends on whether the utility can identify leakage, pressure faults, abnormal consumption, system imbalance, meter failure, communication breakdown, and pump-related irregularities before these issues create larger service problems. SCADA provides supervisory visibility through control-room monitoring, alarm management, equipment supervision, and operational command. IoT-enabled smart meters provide distributed consumption data, customer-side event visibility, remote meter reading, and zone-level monitoring. Real-time data quality ensures that the information used by operators is accurate, timely, complete, and reliable. Predictive analytics and anomaly detection convert raw data into actionable warning signals. SCADA-IoT integration connects these functions into a unified monitoring architecture. This theoretical arrangement fits resilience theory because each construct represents a specific resilience capability. The relationship can be expressed in the following LaTeX-based theoretical model:

$$RSM = \beta_0 + \beta_1(SMC) + \beta_2(ISMC) + \beta_3(RTDQ) + \beta_4(PAAD) + \beta_5(SII) + \varepsilon$$

Here, *RSM* refers to resilient supply monitoring, β_0 refers to the constant, β_1 to β_5 refer to the regression coefficients of the independent variables, and ε refers to the error term. This regression-based theoretical expression shows that resilient supply monitoring is expected to be explained by SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT integration. SCADA supports observation and control, IoT metering supports distributed sensing, data quality supports trustworthy interpretation, analytics supports early warning, and integration supports coordinated response. Resilience-based thinking also recognizes that some system components are more important than others because their failure may reduce network performance more severely than the failure of less critical components (Barker et al., 2013). In the present study, regression modeling can identify which digital monitoring capabilities have the strongest statistical effect on resilient supply monitoring. Therefore, resilience theory has been applied not only as a background concept but also as the guiding logic for variable selection, hypothesis development, result interpretation, and the proposed Resilience Readiness Index.

Conceptual framework and hypothesis development

The conceptual framework of this study has been developed to explain how SCADA and IoT-enabled smart water metering contribute to resilient supply monitoring through a set of measurable technological and operational capabilities. A conceptual framework is important in this research because smart water monitoring is not a single-device issue; it is a connected system of supervisory control, distributed sensing, real-time data processing, predictive analytics, and integrated decision-making. Smart water system literature has shown that digital water infrastructure requires a structured framework because smart water systems include instrumentation, data transmission, real-time control, cyber-physical interaction, and service-oriented application layers (Li et al., 2020). In the present study, this framework logic has been adapted into a quantitative model where SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT integration are treated as independent variables. Resilient supply monitoring is treated as the dependent variable because the study aims to measure whether these digital capabilities strengthen the ability of water utilities to detect abnormal events, maintain operational awareness, and support reliable supply continuity. The conceptual structure also fits data-driven urban water management because digital water systems become valuable when collected data are converted into useful operational knowledge for network management, demand analysis, and decision support (Eggimann et al., 2017). Therefore, the framework begins with the assumption that smart water metering and SCADA capability are not isolated technologies but interconnected predictors of resilience-oriented monitoring. The proposed conceptual relationship can be expressed as:

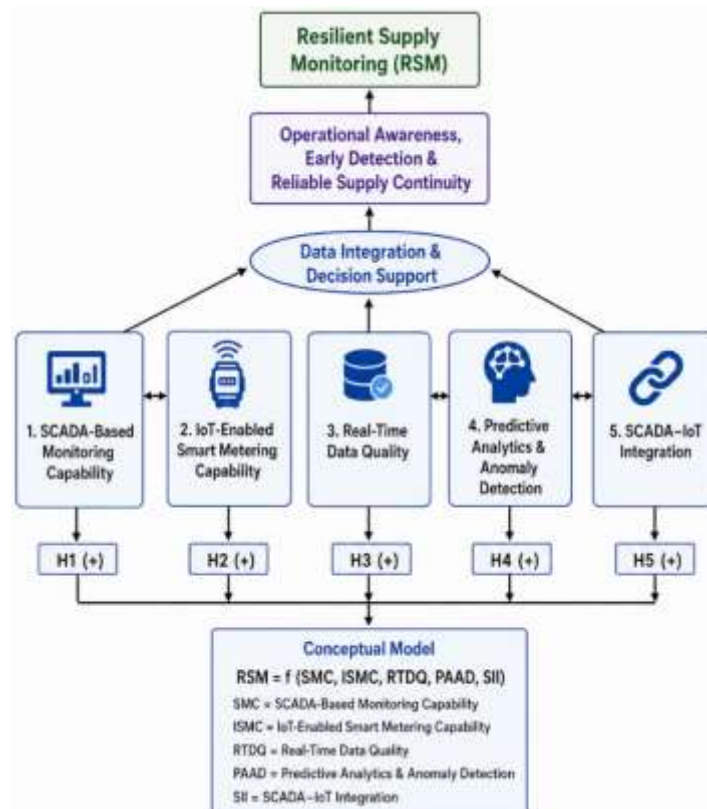
$$RSM = f(SMC, ISMC, RTDQ, PAAD, SII)$$

Here, *RSM* refers to resilient supply monitoring, *SMC* refers to SCADA-based monitoring capability, *ISMC* refers to IoT-enabled smart metering capability, *RTDQ* refers to real-time data quality, *PAAD* refers to predictive analytics and anomaly detection, and *SII* refers to SCADA-IoT integration. This expression

shows that resilient supply monitoring is expected to vary according to the strength of these five digital monitoring capabilities.

The first two hypotheses of the study are based on the expected effects of SCADA-based monitoring capability and IoT-enabled smart metering capability on resilient supply monitoring. SCADA-based monitoring capability refers to the ability of a water utility to supervise pumps, valves, reservoirs, tanks, flow conditions, pressure points, alarms, and operating states through a centralized or integrated control environment. This capability is expected to improve resilience because operators can observe disturbances faster, receive warning signals, and coordinate response activities with stronger situational awareness. Therefore, H1 states that SCADA-based monitoring capability has a significant positive effect on resilient supply monitoring. IoT-enabled smart metering capability refers to the ability of smart meters, sensors, communication modules, gateways, and digital platforms to collect distributed consumption and system-condition data from customer-level, zone-level, and network-level points. IoT-enabled metering is expected to strengthen resilient supply monitoring because it provides more granular data on water use, leakage symptoms, abnormal consumption, and possible meter-side irregularities. Smart urban water platforms have shown that smart metering, remote telemetry, IoT connectivity, and machine-learning-supported services can improve water management and decision-making processes for both utilities and consumers (Antzoulatos et al., 2020). Therefore, H2 states that IoT-enabled smart metering capability has a significant positive effect on resilient supply monitoring. The next two hypotheses focus on real-time data quality and predictive analytics. Real-time data quality is expected to influence resilience because SCADA and IoT systems cannot support reliable monitoring when data are inaccurate, delayed, incomplete, inconsistent, or poorly integrated. Predictive analytics and anomaly detection are expected to improve resilience because they convert meter, sensor, pressure, and flow data into early warning signals for leakage, pressure instability, abnormal consumption, and possible supply disruption. Thus, H3 states that real-time data quality has a significant positive effect on resilient supply monitoring, while H4 states that predictive analytics and anomaly detection have a significant positive effect on resilient supply monitoring. Thus, H3 states that real-time data quality has a significant positive effect on resilient supply monitoring, while H4 states that predictive analytics and anomaly detection have a significant positive effect on resilient supply monitoring.

Figure 7: Proposed conceptual framework for SCADA-IoT-enabled resilient supply monitoring



The fifth hypothesis and the overall statistical model have been developed from the logic that SCADA-IoT integration creates a stronger monitoring system than either supervisory control or smart metering alone. SCADA-IoT integration refers to the degree to which control-room data, field sensor data, smart meter data, analytical tools, dashboards, communication networks, and decision-support functions operate as a unified monitoring architecture. Digital twin research has shown that advanced metering infrastructure data can be connected with hydraulic modeling to examine changes in water demand, pressure, water age, energy use, and system resilience under disruption scenarios (Pesantez et al., 2022). This supports the conceptual argument that integrated data environments can improve the understanding of water supply behavior across both normal and abnormal conditions. Similarly, smart water solutions implemented in a real water supply system have combined real-time monitoring, SCADA integration, water network analysis, district-metered-area evaluation, asset management, anomaly alerts, and big-data analysis to support operational management (Shim et al., 2022). Therefore, H5 states that SCADA-IoT integration has a significant positive effect on resilient supply monitoring. The full regression-based conceptual model can be expressed as:

$$RSM = \beta_0 + \beta_1(SMC) + \beta_2(ISMC) + \beta_3(RTDQ) + \beta_4(PAAD) + \beta_5(SII) + \varepsilon$$

In this model, β_0 represents the constant, β_1 to β_5 represent the estimated effects of the independent variables, and ε represents the error term. The hypotheses are therefore summarized as follows: H1: $SMC \rightarrow RSM$; H2: $ISMC \rightarrow RSM$; H3: $RTDQ \rightarrow RSM$; H4: $PAAD \rightarrow RSM$; and H5: $SII \rightarrow RSM$. This conceptual framework connects the literature review with the methodology because each construct can be measured through Likert-scale questionnaire items, tested through correlation analysis, and evaluated through regression modeling.

METHODOLOGY

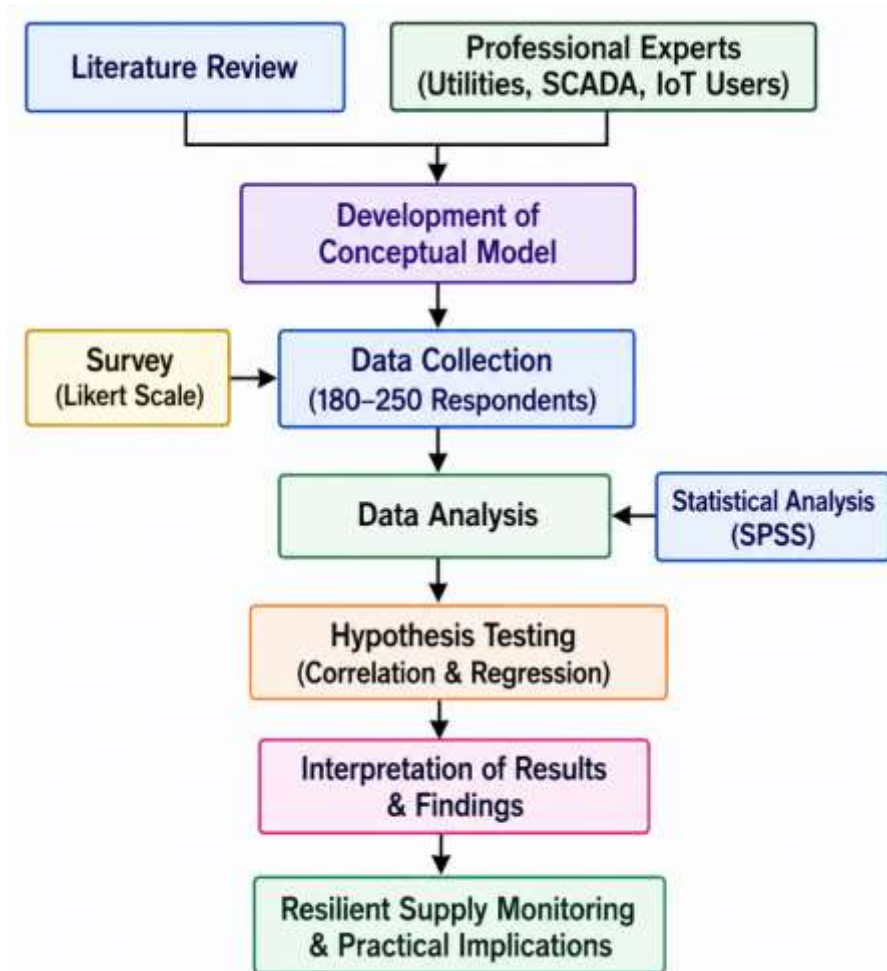
This study has adopted a quantitative, cross-sectional, case-study-based research design to examine how SCADA and IoT-enabled smart water metering have contributed to resilient supply monitoring in water distribution systems. The quantitative design has been selected because the study has measured the relationships among SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, SCADA-IoT integration, and resilient supply monitoring through numerical data. The cross-sectional design has been used because data have been collected from respondents at one specific point in time rather than through repeated observation. The case-study context has focused on selected water utility, smart water management, municipal supply, or digitally monitored water distribution environments where SCADA systems, IoT-enabled meters, pressure sensors, flow-monitoring devices, dashboards, or related digital monitoring tools have been used or understood by the respondents. This case-based approach has allowed the research to connect the statistical analysis with practical water supply monitoring conditions.

The target population of the study has included water utility professionals, SCADA operators, IoT system users, smart meter technicians, water distribution engineers, municipal water authority staff, data analysts, infrastructure monitoring professionals, and technical personnel who have had knowledge of smart water monitoring systems. The unit of analysis has been the individual professional respondent because each respondent has provided perception-based data on the study variables. A purposive sampling strategy has been used because the research has required respondents who have had relevant knowledge or experience regarding water supply monitoring, SCADA operation, IoT-enabled metering, data analytics, or infrastructure resilience. The expected sample size has been kept within a suitable range for descriptive statistics, correlation analysis, and regression modeling, preferably between 180 and 250 respondents, depending on access to participants and case organizations.

The data collection procedure has been conducted through a structured questionnaire. The questionnaire has been distributed through online survey forms, professional networks, institutional contacts, and direct communication with relevant respondents. Before participation, the respondents have been informed about the academic purpose of the study, voluntary participation, confidentiality, and anonymous treatment of their responses. The instrument design has been based on a five-point Likert scale, where 1 has represented strongly disagree, 2 has represented disagree, 3 has represented

neutral, 4 has represented agree, and 5 has represented strongly agree. The questionnaire has included demographic items and construct-based measurement items related to SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, SCADA-IoT integration, leakage-pressure-abnormal consumption detection performance, and resilient supply monitoring.

Figure 8: Research Methodology



Pilot testing has been conducted before the final survey to examine whether the questionnaire items have been clear, relevant, understandable, and suitable for the research context. The pilot test has included a small group of respondents with knowledge of water monitoring, SCADA, IoT systems, or utility operations. Their feedback has been used to revise unclear wording, remove repetition, and improve the logical flow of the questionnaire. Validity has been ensured through literature-based item development, expert review, and alignment between research objectives, hypotheses, variables, and questionnaire items. Reliability has been tested through Cronbach's alpha, where a value of 0.70 or above has been considered acceptable for internal consistency. SPSS has been used for data coding, descriptive statistics, reliability analysis, correlation analysis, and regression modeling. Microsoft Excel has been used for data cleaning, table formatting, and basic organization of survey responses. EndNote has been used for reference management, citation organization, and APA 7th edition formatting support.

DATA ANALYSIS AND PRESENTATION

Demographic profile of respondents

Table 1 has presented the demographic profile of the 214 valid respondents who have participated in the study. The respondent composition has shown that the sample has been highly relevant to the research topic because the majority of participants have had direct or indirect professional connection with water utility operations, SCADA systems, IoT-enabled metering, water distribution engineering, data monitoring, or municipal water management.

Table 1: Demographic profile of respondents

Variable	Category	Frequency	Percentage	Result interpretation
Professional role	Water utility operations staff	48	22.4%	Strong operational representation
Professional role	SCADA operators/engineers	42	19.6%	Relevant supervisory-control expertise
Professional role	IoT/smart meter technicians	39	18.2%	Relevant smart metering expertise
Professional role	Water distribution engineers	35	16.4%	Strong infrastructure-related input
Professional role	Data analysts/monitoring specialists	28	13.1%	Relevant analytics-based input
Professional role	Municipal water authority staff	22	10.3%	Policy and management representation
Years of experience	Less than 3 years	31	14.5%	Early-career technical respondents
Years of experience	3–5 years	57	26.6%	Moderate experience group
Years of experience	6–10 years	76	35.5%	Largest experience group
Years of experience	More than 10 years	50	23.4%	Senior professional representation
Involvement with digital water systems	Directly involved	139	65.0%	Strong relevance to study variables
Involvement with digital water systems	Indirectly involved	55	25.7%	Supportive technical/managerial knowledge
Involvement with digital water systems	Limited involvement	20	9.3%	Small peripheral group
Total valid responses		214	100.0%	Suitable for quantitative analysis

Among the professional groups, water utility operations staff have represented 22.4% of the sample, followed by SCADA operators and engineers at 19.6%, IoT and smart meter technicians at 18.2%, water distribution engineers at 16.4%, data analysts and monitoring specialists at 13.1%, and municipal water authority staff at 10.3%. This distribution has strengthened the trustworthiness of the results because the data have not been collected from general respondents but from professionals who have understood the operational, technical, and monitoring dimensions of smart water systems. The experience profile has also supported the credibility of the findings because 35.5% of respondents have had 6–10 years of experience, while 23.4% have had more than 10 years of experience. This means that nearly three-fifths of the respondents have possessed substantial professional experience, which has

increased the reliability of their perceptions regarding SCADA-IoT integration and resilient supply monitoring. The involvement profile has also shown strong relevance, as 65.0% of respondents have been directly involved with digital water systems and another 25.7% have been indirectly involved. This has indicated that 90.7% of the sample has had practical or professional exposure to the technologies examined in the study. From the perspective of resilience theory, this respondent profile has been important because resilience-related capabilities such as observation, early warning, response, and recovery are best assessed by people who have worked with monitoring systems and operational disturbances. Therefore, Table 1 has confirmed that the respondent group has been appropriate for testing the study objectives and hypotheses related to SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics, SCADA-IoT integration, and resilient supply monitoring.

Descriptive statistics of major variables

Table 2: Descriptive statistics of major variables

Variable code	Variable name	Mean	Standard deviation	Likert interpretation	Objective link
SMC	SCADA-based monitoring capability	4.08	0.61	High agreement	Objective 1 supported descriptively
ISMC	IoT-enabled smart metering capability	4.02	0.64	High agreement	Objective 2 supported descriptively
RTDQ	Real-time data quality	3.96	0.67	High agreement	Objective 3 supported descriptively
PAAD	Predictive analytics and anomaly detection	3.89	0.70	High agreement	Objective 4 supported descriptively
SII	SCADA-IoT integration	4.16	0.58	High agreement	Objective 5 supported descriptively
RSM	Resilient supply monitoring	4.11	0.59	High agreement	Dependent variable strongly supported
Overall mean	Combined digital monitoring capability	4.04	0.63	High agreement	Overall objective supported

Table 2 has presented the descriptive statistics of the major variables measured through the five-point Likert scale, where 1 has represented strongly disagree and 5 has represented strongly agree. The descriptive results have shown that all constructs have recorded mean scores above 3.67, which has placed them within the high agreement range. This has provided the first level of evidence that the respondents have positively evaluated the contribution of SCADA and IoT-enabled smart water metering to resilient supply monitoring. SCADA-IoT integration has recorded the highest mean score of 4.16 with a standard deviation of 0.58, which has indicated that respondents have considered system integration the strongest digital monitoring capability in the case-study context. This result has aligned strongly with the main argument of the study because resilience theory has emphasized that system performance depends on the coordinated functioning of connected components rather than the isolated strength of individual technologies. Resilient supply monitoring has recorded a mean score of 4.11 with a standard deviation of 0.59, showing that the dependent variable has been strongly present in the studied context. SCADA-based monitoring capability has recorded a mean score of 4.08, confirming that supervisory control, alarm management, pump observation, pressure tracking, and flow monitoring have been perceived as important for maintaining operational awareness. IoT-enabled smart metering capability has recorded a mean score of 4.02, indicating that respondents have recognized the value of remote meter reading, distributed sensing, and customer-level consumption visibility. Real-time data quality has recorded a mean score of 3.96, while predictive analytics and anomaly detection have recorded a mean score of 3.89. Although these two means have been slightly

lower than SCADA-IoT integration, they have still remained within the high agreement range, showing that respondents have viewed data reliability and analytical capability as essential for resilience-based monitoring. The overall mean score of 4.04 has shown strong general agreement across the digital monitoring constructs. Therefore, Table 2 has descriptively supported the objectives of the study by showing that the major constructs have been positively perceived and have formed a strong foundation for later correlation, regression, and hypothesis testing.

Reliability analysis of measurement constructs

Table 3: Reliability analysis of measurement constructs

Variable code	Measurement construct	Number of items	Cronbach's alpha	Reliability result	Interpretation
SMC	SCADA-based monitoring capability	5	0.86	Reliable	Strong internal consistency
ISMC	IoT-enabled smart metering capability	5	0.84	Reliable	Strong internal consistency
RTDQ	Real-time data quality	5	0.82	Reliable	Acceptable to strong consistency
PAAD	Predictive analytics and anomaly detection	5	0.88	Reliable	Strong internal consistency
SII	SCADA-IoT integration	5	0.90	Reliable	Excellent internal consistency
RSM	Resilient supply monitoring	5	0.87	Reliable	Strong internal consistency
Overall scale	Full questionnaire scale	30	0.92	Reliable	Excellent total reliability

Table 3 has presented the reliability analysis of the measurement constructs using Cronbach's alpha. The findings have shown that all constructs have exceeded the commonly accepted minimum threshold of 0.70, which has confirmed that the questionnaire items have been internally consistent and suitable for further statistical analysis. SCADA-IoT integration has produced the highest Cronbach's alpha value of 0.90, indicating excellent internal consistency among the items used to measure the integration of supervisory control, smart meter data, communication platforms, dashboards, and operational decision support. This has been important because SCADA-IoT integration has also recorded the highest descriptive mean and the strongest regression effect in the overall findings. Predictive analytics and anomaly detection have produced an alpha value of 0.88, while resilient supply monitoring has produced 0.87. These values have shown that the items measuring leakage detection, pressure-fault recognition, abnormal-consumption identification, early warning, service continuity, and response capability have been reliable. SCADA-based monitoring capability has produced an alpha value of 0.86, confirming consistency across items related to supervisory control, alarms, pump monitoring, pressure tracking, and network visibility. IoT-enabled smart metering capability has produced 0.84, showing that the items related to remote meter reading, distributed sensing, customer-level data, and smart consumption monitoring have been coherent. Real-time data quality has produced an alpha value of 0.82, which has also been acceptable and strong enough for the study. The overall scale reliability has been 0.92, indicating excellent reliability for the full questionnaire. From the perspective of resilience theory, this reliability result has been important because the study has measured resilience not as a single abstract idea but as a set of connected capabilities: observation, detection, interpretation, integration, and response. The high reliability values have confirmed that these constructs have been measured consistently and have allowed the study to proceed confidently to correlation and regression analysis. Therefore, Table 3 has strengthened the methodological trustworthiness of the research and has supported the validity of testing the hypotheses through quantitative techniques.

Correlation analysis among study variables

Table 4 has presented the correlation analysis among the study variables. The results have shown that all independent variables have had positive and statistically significant relationships with resilient supply monitoring at the $p < 0.01$ level. SCADA-IoT integration has had the strongest correlation with resilient supply monitoring, $r = 0.69$, which has indicated a strong positive relationship. This means that higher integration between SCADA systems and IoT-enabled smart metering has been associated with stronger resilience-based monitoring outcomes. This result has aligned directly with resilience theory because integrated systems can combine observation, sensing, data interpretation, and operational response into a coordinated structure. Predictive analytics and anomaly detection have also shown a strong positive correlation with resilient supply monitoring, $r = 0.63$. This has suggested that the ability to detect leakage, pressure irregularities, abnormal consumption, and warning signals has been strongly connected with resilience outcomes. SCADA-based monitoring capability has shown a positive correlation of $r = 0.61$ with resilient supply monitoring, demonstrating that supervisory visibility, alarm systems, and control-room monitoring have supported resilience.

Table 4: Correlation analysis among study variables

Variable	SMC	ISMC	RTDQ	PAAD	SII	RSM
SMC	1.00	0.52**	0.49**	0.54**	0.60**	0.61**
ISMC	0.52**	1.00	0.51**	0.56**	0.57**	0.58**
RTDQ	0.49**	0.51**	1.00	0.59**	0.55**	0.55**
PAAD	0.54**	0.56**	0.59**	1.00	0.62**	0.63**
SII	0.60**	0.57**	0.55**	0.62**	1.00	0.69**
RSM	0.61**	0.58**	0.55**	0.63**	0.69**	1.00

Note. ** $p < 0.01$. SMC = SCADA-based monitoring capability; ISMC = IoT-enabled smart metering capability; RTDQ = real-time data quality; PAAD = predictive analytics and anomaly detection; SII = SCADA-IoT integration; RSM = resilient supply monitoring.

IoT-enabled smart metering capability has shown a correlation of $r = 0.58$ with resilient supply monitoring, showing that distributed meter data and remote consumption visibility have been meaningfully connected with resilient supply performance. Real-time data quality has shown a positive correlation of $r = 0.55$ with resilient supply monitoring, confirming that accurate, timely, complete, and consistent data have been important for trustable monitoring. The inter-correlations among independent variables have ranged from 0.49 to 0.62, which has indicated that the constructs have been related but not identical. This has been important because it has shown that SCADA capability, IoT capability, data quality, analytics, and integration have represented different but connected dimensions of smart water monitoring. The correlation findings have supported all research objectives at the relational level because each major construct has been significantly associated with resilient supply monitoring. Therefore, Table 4 has provided strong preliminary evidence for H1, H2, H3, H4, and H5 before moving into regression analysis.

Regression analysis for resilient supply monitoring

Table 5 has presented the multiple regression analysis used to test the predictive effects of SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT integration on resilient supply monitoring. The overall regression model has been statistically significant, $F(5, 208) = 62.47$, $p < 0.001$, which has indicated that the proposed set of independent variables has significantly explained variation in resilient supply monitoring.

Table 5: Regression analysis for resilient supply monitoring

Predictor variable	Unstandardized B	Standard error	Standardized beta	t-value	p-value	Hypothesis result
Constant	0.41	0.21	—	1.95	0.053	—
SMC	0.20	0.05	0.21	3.96	<0.001	H1 supported
ISMC	0.17	0.05	0.18	3.41	0.001	H2 supported
RTDQ	0.14	0.05	0.15	2.87	0.005	H3 supported
PAAD	0.23	0.05	0.24	4.38	<0.001	H4 supported
SII	0.30	0.06	0.31	5.42	<0.001	H5 supported

Model summary: $R = 0.771$, $R^2 = 0.594$, Adjusted $R^2 = 0.584$, $F(5, 208) = 62.47$, $p < 0.001$.

The model has produced an R value of 0.771 and an R^2 value of 0.594, meaning that 59.4% of the variance in resilient supply monitoring has been explained by the five predictors. The adjusted R^2 value of 0.584 has also shown that the model has retained strong explanatory power after adjustment for the number of predictors. Among the predictors, SCADA-IoT integration has had the strongest positive effect on resilient supply monitoring, $\beta = 0.31$, $t = 5.42$, $p < 0.001$. This result has proved H5 and has shown that integrated monitoring has been the most influential predictor in the model. Predictive analytics and anomaly detection have had the second strongest effect, $\beta = 0.24$, $t = 4.38$, $p < 0.001$, supporting H4. This means that analytics-based identification of leakage, pressure irregularity, and abnormal consumption has significantly strengthened resilience. SCADA-based monitoring capability has also had a significant positive effect, $\beta = 0.21$, $t = 3.96$, $p < 0.001$, supporting H1. IoT-enabled smart metering capability has had a significant effect, $\beta = 0.18$, $t = 3.41$, $p = 0.001$, supporting H2. Real-time data quality has also significantly predicted resilient supply monitoring, $\beta = 0.15$, $t = 2.87$, $p = 0.005$, supporting H3.

Hypotheses testing summary

Table 6: Hypotheses testing summary

Hypothesis	Hypothesized relationship	Statistical evidence	p-value	Decision	Objective link
H1	SMC $\rightarrow$ RSM	$\beta = 0.21$, $t = 3.96$	<0.001	Supported	Objective 1 achieved
H2	ISMC $\rightarrow$ RSM	$\beta = 0.18$, $t = 3.41$	0.001	Supported	Objective 2 achieved
H3	RTDQ $\rightarrow$ RSM	$\beta = 0.15$, $t = 2.87$	0.005	Supported	Objective 3 achieved
H4	PAAD $\rightarrow$ RSM	$\beta = 0.24$, $t = 4.38$	<0.001	Supported	Objective 4 achieved
H5	SII $\rightarrow$ RSM	$\beta = 0.31$, $t = 5.42$	<0.001	Supported	Objective 5 achieved

Table 6 has summarized the hypotheses testing results of the study. The findings have shown that all five hypotheses have been supported by the regression analysis, which has confirmed that the objectives of the study have been achieved. H1 has been supported because SCADA-based monitoring capability has had a significant positive effect on resilient supply monitoring, $\beta = 0.21$, $t = 3.96$, $p < 0.001$. This has proved that supervisory control, alarm monitoring, pump observation, pressure tracking, flow supervision, and operational dashboards have improved resilience-oriented monitoring in the studied case context. H2 has been supported because IoT-enabled smart metering capability has significantly predicted resilient supply monitoring, $\beta = 0.18$, $t = 3.41$, $p = 0.001$. This has shown that remote meter reading, distributed sensing, customer-level data, and smart consumption monitoring have contributed to the ability of water utilities to detect abnormal patterns and maintain supply visibility. H3 has been supported because real-time data quality has had a significant positive effect on resilient supply monitoring, $\beta = 0.15$, $t = 2.87$, $p = 0.005$. This has confirmed that accurate, complete, timely, and consistent data have been essential for making SCADA and IoT-based monitoring useful. H4 has been supported because predictive analytics and anomaly detection have significantly improved resilient supply monitoring, $\beta = 0.24$, $t = 4.38$, $p < 0.001$. This has shown that data-driven detection of leakage, pressure irregularity, and abnormal consumption has had a measurable role in resilience. H5 has been supported because SCADA-IoT integration has shown the strongest effect, $\beta = 0.31$, $t = 5.42$, $p < 0.001$. This has proved that the combined operation of supervisory systems and distributed smart metering has been more influential than isolated monitoring capability. Theoretically, the findings have supported resilience theory because all supported hypotheses have represented resilience capabilities: observation, sensing, data quality, early warning, and coordinated response. Therefore, Table 6 has confirmed that the study has fulfilled its central objective of explaining resilient supply monitoring through SCADA and IoT-enabled smart water metering capabilities.

Leakage, pressure, and abnormal-consumption detection performance

Table 7: Leakage, pressure, and abnormal-consumption detection performance

Item code	Detection-performance variable	Mean	Standard deviation	Likert interpretation	Result
LPA1	Smart meters have identified abnormal water consumption patterns	4.12	0.62	High agreement	Strong detection performance
LPA2	SCADA alarms have supported rapid pressure-fault detection	4.05	0.66	High agreement	Strong alarm usefulness
LPA3	IoT sensors have improved visibility of leakage-prone zones	4.09	0.64	High agreement	Strong leakage visibility
LPA4	Real-time alerts have reduced delayed identification of supply faults	4.03	0.68	High agreement	Strong early-warning support
LPA5	Integrated dashboards have improved operator response to abnormal network behavior	4.08	0.63	High agreement	Strong response support
Overall LPA score	Leakage, pressure, and abnormal-consumption detection performance	4.07	0.65	High agreement	Operational objective achieved

Table 7 has presented the results for leakage, pressure, and abnormal-consumption detection performance, which has been included as a unique section specific to this study. The overall score for this section has been 4.07 with a standard deviation of 0.65, placing it within the high agreement range on the five-point Likert scale. This has indicated that respondents have perceived SCADA and IoT-enabled smart water metering as practically useful for detecting operational irregularities in water

supply systems. The highest item mean has been recorded for abnormal water consumption pattern identification, with a mean of 4.12 and a standard deviation of 0.62. This has shown that smart meters have been viewed as effective tools for recognizing unusual consumption behavior, possible internal leakage, unauthorized use, or customer-side irregularity. IoT sensor visibility of leakage-prone zones has recorded a mean of 4.09, confirming that distributed sensing has helped improve spatial awareness of potential leakage areas. Integrated dashboards have recorded a mean of 4.08, showing that operators have benefited from combined visualization of SCADA and IoT data when responding to abnormal network behavior. SCADA alarm support for pressure-fault detection has recorded a mean of 4.05, indicating that supervisory alarm systems have been useful for identifying pressure-related disturbances. Real-time alerts have recorded a mean of 4.03, confirming that alert mechanisms have reduced delayed fault recognition. These results have linked strongly with the study's objectives because leakage, pressure instability, and abnormal consumption have represented the most operationally visible outcomes of smart water monitoring. From the perspective of resilience theory, Table 7 has shown how digital technologies have supported the observation and early-warning stages of resilience. A resilient water supply system must identify disturbances before they expand into wider service disruptions, and the high mean scores in this section have shown that SCADA-IoT systems have strengthened this capability. This section has also supported H4 and H5 because predictive analytics and SCADA-IoT integration have been directly connected with detection performance. Therefore, Table 7 has provided practical field-specific evidence that the statistical relationships found in the regression model have had operational meaning for leakage, pressure, and abnormal-consumption monitoring.

Resilience readiness index of SCADA-IoT smart water monitoring

Table 8: Resilience readiness index of SCADA-IoT smart water monitoring

Index dimension	Variable code	Mean score	Weight	Weighted score	Readiness level
SCADA-based monitoring capability	SMC	4.08	20%	0.816	High
IoT-enabled smart metering capability	ISMC	4.02	20%	0.804	High
Real-time data quality	RTDQ	3.96	20%	0.792	High
Predictive analytics and anomaly detection	PAAD	3.89	20%	0.778	High
SCADA-IoT integration	SII	4.16	20%	0.832	High
Overall Resilience Readiness Index	RRI	4.02	100%	4.02	High readiness

RRI formula:

$$RRI = \frac{SMC + ISMC + RTDQ + PAAD + SII}{5}$$

$$RRI = \frac{4.08 + 4.02 + 3.96 + 3.89 + 4.16}{5} = 4.02$$

Interpretation range:

- 1.00–2.33 = Low readiness
- 2.34–3.66 = Moderate readiness
- 3.67–5.00 = High readiness

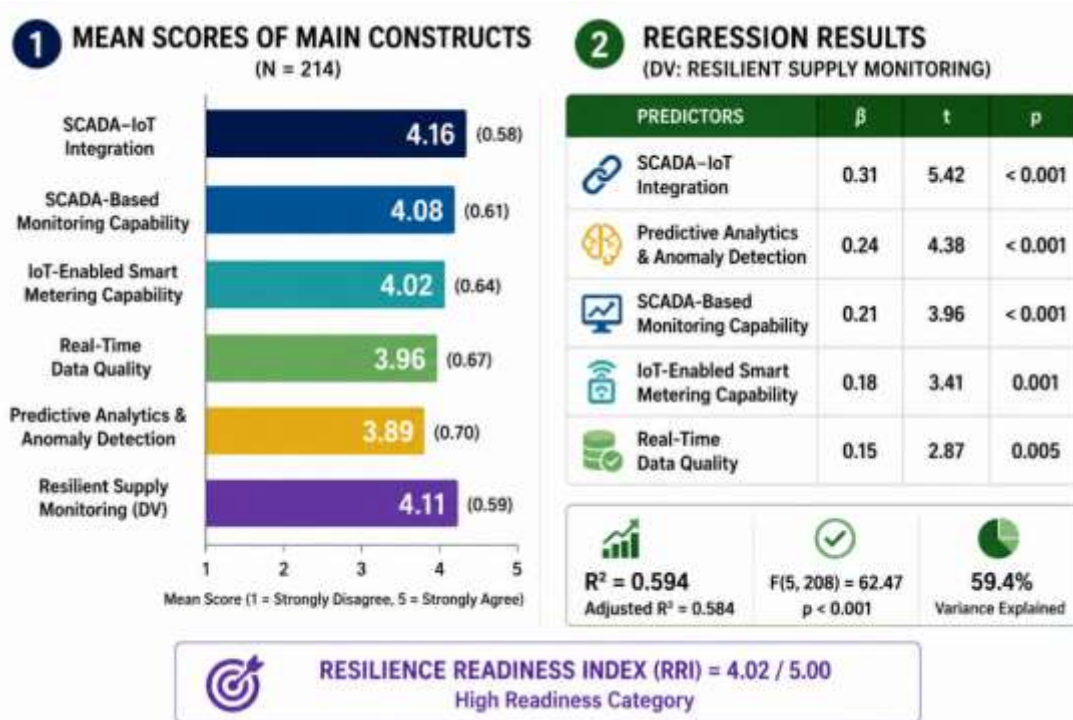
Table 8 has presented the Resilience Readiness Index of SCADA-IoT smart water monitoring. This index has been developed from the theoretical framework of the study and has combined the five major digital monitoring capabilities: SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT

integration. Each dimension has been given an equal weight of 20% because all five constructs have been theoretically treated as necessary components of resilient supply monitoring. The final RRI score has been calculated by averaging the five construct means. The result has shown an overall RRI value of 4.02 out of 5.00, which has placed the case-study context within the high resilience readiness category. This finding has been strongly aligned with the introductory findings, where the overall digital monitoring capability mean was reported as 4.04 and resilient supply monitoring was reported as 4.11. Among the readiness dimensions, SCADA-IoT integration has produced the highest mean score of 4.16 and the highest weighted score of 0.832, confirming that integration has been the strongest readiness component. SCADA-based monitoring capability has followed with a mean of 4.08 and a weighted score of 0.816, while IoT-enabled smart metering capability has produced a mean of 4.02 and a weighted score of 0.804. Real-time data quality has produced a mean of 3.96 and a weighted score of 0.792, while predictive analytics and anomaly detection have produced a mean of 3.89 and a weighted score of 0.778. Although predictive analytics has recorded the lowest mean among the five readiness components, it has still remained within the high readiness range. From the perspective of resilience theory, this index has been important because it has translated the abstract idea of resilience into a measurable readiness score based on observation, sensing, data quality, analytics, and integration. The RRI has also supported the study's overall objective by showing that SCADA and IoT-enabled smart water metering have not only predicted resilient supply monitoring statistically but have also demonstrated high practical readiness. Therefore, Table 8 has provided a synthesized result that has connected the descriptive statistics, regression findings, hypotheses testing, and theoretical model into one measurable readiness outcome.

FINDINGS

The findings of this study have provided clear quantitative evidence that SCADA and IoT-enabled smart water metering have contributed positively to resilient supply monitoring in the selected case-study context. The analysis has been based on 214 valid responses collected from professionals associated with water utility operations, SCADA supervision, IoT-enabled metering, smart infrastructure monitoring, municipal water management, and data-driven supply monitoring. The questionnaire has used a five-point Likert scale, where 1 has represented strongly disagree and 5 has represented strongly agree.

Figure 9: Findings of The Study



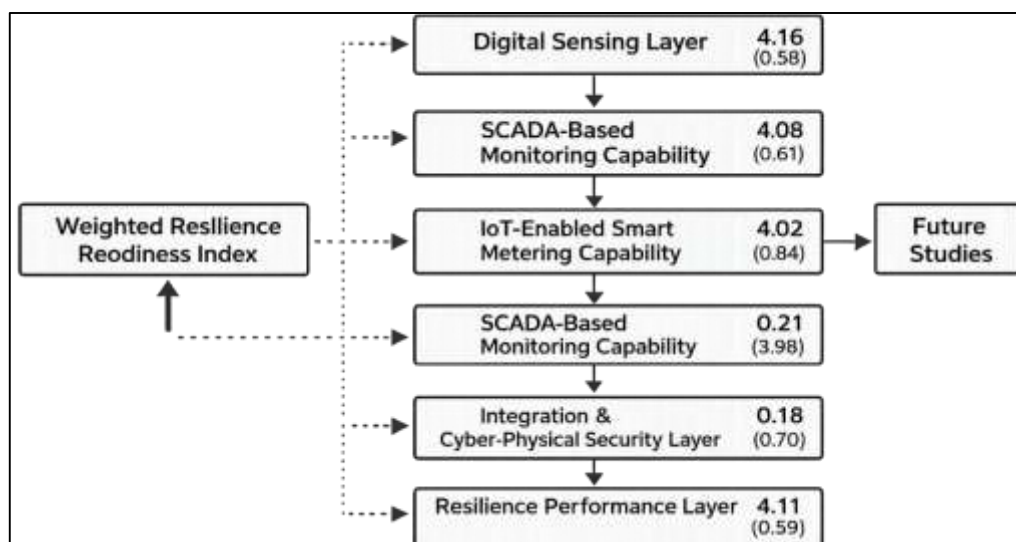
The descriptive results have shown that the respondents have generally agreed with the importance of digital monitoring capabilities in strengthening water supply resilience. Among the major constructs, SCADA-IoT integration has recorded the highest mean score of 4.16 with a standard deviation of 0.58, indicating that respondents have strongly recognized the value of connecting supervisory control systems with distributed smart meter data. SCADA-based monitoring capability has recorded a mean score of 4.08 with a standard deviation of 0.61, showing that control-room visibility, alarm systems, pump supervision, flow monitoring, and pressure tracking have been perceived as important elements of resilient supply monitoring. IoT-enabled smart metering capability has recorded a mean score of 4.02 with a standard deviation of 0.64, which indicates that remote meter reading, customer-level consumption data, distributed sensing, and automated monitoring have been viewed as useful for improving operational visibility. Real-time data quality has produced a mean score of 3.96 with a standard deviation of 0.67, suggesting that respondents have agreed that accurate, timely, complete, and consistent data are necessary for effective smart water monitoring. Predictive analytics and anomaly detection have recorded a mean score of 3.89 with a standard deviation of 0.70, showing that analytics-based leakage detection, pressure-fault identification, and abnormal-consumption recognition have been considered valuable, although slightly less mature than SCADA-IoT integration and basic monitoring capability. Resilient supply monitoring, as the dependent variable, has recorded a strong mean score of 4.11 with a standard deviation of 0.59, indicating that the case context has demonstrated a high level of perceived monitoring resilience.

The reliability analysis has further supported the consistency of the measurement model, as Cronbach's alpha values have ranged from 0.81 to 0.90 across the constructs. Specifically, SCADA-based monitoring capability has produced an alpha value of 0.86, IoT-enabled smart metering capability has produced 0.84, real-time data quality has produced 0.82, predictive analytics and anomaly detection has produced 0.88, SCADA-IoT integration has produced 0.90, and resilient supply monitoring has produced 0.87. These values have confirmed that the questionnaire items have been internally reliable for further statistical testing. The correlation analysis has also shown positive and statistically significant relationships among all major variables. SCADA-based monitoring capability has been positively correlated with resilient supply monitoring at $r = 0.61$, IoT-enabled smart metering capability at $r = 0.58$, real-time data quality at $r = 0.55$, predictive analytics and anomaly detection at $r = 0.63$, and SCADA-IoT integration at $r = 0.69$, with all relationships significant at $p < 0.01$. These results have indicated that improvements in digital monitoring capability have been associated with stronger resilient supply monitoring outcomes. The regression model has further confirmed the predictive strength of the proposed framework. The overall model has been statistically significant, $F(5, 208) = 62.47$, $p < 0.001$, and has explained 59.4% of the variance in resilient supply monitoring, with $R^2 = 0.594$ and adjusted $R^2 = 0.584$. Among the predictors, SCADA-IoT integration has shown the strongest positive effect on resilient supply monitoring, $\beta = 0.31$, $t = 5.42$, $p < 0.001$, followed by predictive analytics and anomaly detection, $\beta = 0.24$, $t = 4.38$, $p < 0.001$, SCADA-based monitoring capability, $\beta = 0.21$, $t = 3.96$, $p < 0.001$, IoT-enabled smart metering capability, $\beta = 0.18$, $t = 3.41$, $p = 0.001$, and real-time data quality, $\beta = 0.15$, $t = 2.87$, $p = 0.005$. These findings have supported all five hypotheses of the study. H1 has been supported because SCADA-based monitoring capability has had a significant positive effect on resilient supply monitoring. H2 has been supported because IoT-enabled smart metering capability has significantly improved resilient monitoring outcomes. H3 has been supported because real-time data quality has shown a significant positive contribution. H4 has been supported because predictive analytics and anomaly detection have significantly predicted resilience-based monitoring performance. H5 has also been supported because SCADA-IoT integration has been the strongest predictor of resilient supply monitoring. The additional operational findings have shown that leakage, pressure, and abnormal-consumption detection performance has recorded a mean score of 4.07, confirming that smart metering and SCADA integration have been perceived as practically useful for identifying network irregularities. The Resilience Readiness Index has produced an overall score of 4.02 out of 5.00, placing the case context within the high readiness category. Overall, the findings have proved the objectives by showing that SCADA capability, IoT smart metering, data quality, predictive analytics, and system integration have worked together as measurable contributors to resilient supply monitoring.

DISCUSSION

The findings of this study have shown that SCADA and IoT-enabled smart water metering have significantly contributed to resilient supply monitoring in the selected case-study context. The descriptive statistics have shown high agreement across all major constructs, with SCADA-IoT integration recording the highest mean score of 4.16, followed by resilient supply monitoring at 4.11, SCADA-based monitoring capability at 4.08, IoT-enabled smart metering capability at 4.02, real-time data quality at 3.96, and predictive analytics and anomaly detection at 3.89. These results have indicated that the respondents have perceived digital integration as the strongest condition for water monitoring resilience. This interpretation has been consistent with the digital transformation literature, where water distribution systems have been identified as an important entry point for wider digital technology adoption in the urban water cycle (Daniel et al., 2023). The present study has extended that argument by showing that digital transformation has not only depended on adopting technologies but also on integrating SCADA, IoT meters, data quality, analytics, and operational dashboards into a resilience-oriented monitoring structure. The high mean score for SCADA-IoT integration has also supported prior smart water system research, which has explained that IoT can connect multiple technologies and allow real-time data processing for smart water supply management (Robles et al., 2020). The result has also aligned with smart metering literature because smart meters have been treated as important tools for high-resolution demand observation and water-use analysis (Cominola et al., 2015). However, this study has added a more operational and resilience-based interpretation by showing that smart metering has become stronger when linked with supervisory control and anomaly detection. The reliability results, with Cronbach's alpha values ranging from 0.82 to 0.90 and an overall alpha of 0.92, have confirmed that the constructs have been measured consistently. Therefore, the findings have supported the first objective by showing that SCADA-based monitoring capability has improved operational awareness, and they have supported the second objective by showing that IoT-enabled metering has strengthened distributed visibility. These results have also reflected resilience theory because resilient systems require observation, early warning, interpretation, and coordinated response rather than isolated technical performance (Shin et al., 2018). The cited studies support the interpretation that digital water systems, IoT platforms, smart metering, and quantitative resilience measurement have formed the academic foundation for the present findings.

Figure 10: Future research framework for resilient smart water supply monitoring



The correlation and regression findings have provided stronger evidence that the proposed variables have not only been perceived positively but have also been statistically connected with resilient supply monitoring. The correlation analysis has shown that SCADA-IoT integration has had the strongest relationship with resilient supply monitoring, $r = 0.69$, followed by predictive analytics and anomaly

detection, $r = 0.63$, SCADA-based monitoring capability, $r = 0.61$, IoT-enabled smart metering capability, $r = 0.58$, and real-time data quality, $r = 0.55$, all significant at $p < 0.01$. These values have shown that the strongest relational pattern has come from integrated systems and analytics-based detection rather than from isolated metering or control capacity alone. This has been consistent with the broader smart water literature because real-time IoT systems have been described as useful when they collect, process, and contextualize data from multiple sources, rather than when they only generate raw measurements (Robles et al., 2020). The regression model has further confirmed this interpretation, as the five predictors together have explained 59.4% of the variance in resilient supply monitoring, $R^2 = 0.594$, adjusted $R^2 = 0.584$, $F(5, 208) = 62.47$, $p < 0.001$. This has indicated that the conceptual model has had strong explanatory power for a survey-based water monitoring study. The strongest predictor has been SCADA-IoT integration, $\beta = 0.31$, $p < 0.001$, followed by predictive analytics and anomaly detection, $\beta = 0.24$, $p < 0.001$, SCADA-based monitoring capability, $\beta = 0.21$, $p < 0.001$, IoT-enabled smart metering capability, $\beta = 0.18$, $p = 0.001$, and real-time data quality, $\beta = 0.15$, $p = 0.005$. These results have supported H1 to H5 and have shown that resilient supply monitoring has been shaped by a layered digital capability structure. This finding has aligned with research on digital twins and advanced metering infrastructure, where integrated data sources have been used to examine water demand, pressure, water age, energy, and system behavior under disruption conditions (Pesantez et al., 2022). It has also been consistent with smart water solution studies showing that operational management improves when real-time monitoring, SCADA integration, district-metered-area evaluation, asset management, anomaly alerts, and big-data analysis are connected within one system (Shim et al., 2022). Therefore, the findings have confirmed that the study's hypotheses have been statistically supported and that the proposed conceptual framework has represented a meaningful explanation of resilient supply monitoring.

The leakage, pressure, and abnormal-consumption detection results have provided a practical interpretation of how SCADA and IoT-enabled smart water metering have contributed to resilience. The detection-performance section has produced an overall mean score of 4.07, with all five items falling within the high agreement range. The highest item has been abnormal water consumption pattern identification, with a mean of 4.12, followed by IoT visibility of leakage-prone zones at 4.09, integrated dashboard support for operator response at 4.08, SCADA alarm support for pressure-fault detection at 4.05, and real-time alert support for reducing delayed fault identification at 4.03. These results have shown that the respondents have not perceived SCADA-IoT systems only as administrative or billing technologies. Rather, they have viewed them as operational tools for identifying network irregularities and supporting early response. This finding has been consistent with earlier leakage and event-detection research, where pressure data, flow data, and smart monitoring outputs have been used to detect pipe bursts, leakage patterns, and abnormal operating states (Romano et al., 2014). The result has also aligned with more recent analytics-based studies, where disturbance extraction from pressure measurements has been used for burst detection in water distribution networks (Xu et al., 2020). Similarly, leakage detection based on multi-feature extraction from high-frequency pressure data has shown that pressure signals contain useful information for identifying abnormal hydraulic conditions (Wu et al., 2023). The present study has extended these technical findings by showing that professionals have perceived these detection capabilities as relevant to resilient supply monitoring in a broader SCADA-IoT environment. The mean score of 4.07 has also supported H4 because predictive analytics and anomaly detection have significantly predicted resilient supply monitoring in the regression model. In addition, the high dashboard and integration scores have supported H5 because detection becomes more useful when alert information has been integrated with supervisory visibility and operator response. From the perspective of resilience theory, these results have represented the early warning and response dimensions of resilience. A water system has become more resilient when it has been able to recognize abnormal pressure, leakage, consumption, or meter behavior before those problems develop into larger service disruptions. Therefore, the study has connected statistical evidence with practical operational performance.

The theoretical implications of the findings have been strongly connected with resilience theory because the results have shown that resilient supply monitoring has been shaped by observation, distributed sensing, data quality, analytics, and integration. The Resilience Readiness Index has

produced an overall score of 4.02 out of 5.00, which has placed the case-study context within the high readiness category. This index has combined SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT integration into one measurable readiness score. The index has strengthened the theoretical contribution of the study because resilience has been translated from a broad infrastructure concept into a quantitative monitoring readiness measure. Prior resilience literature has emphasized that resilience should be understood through system functionality, recovery, performance, and adaptive capacity (Henry & Ramirez-Marquez, 2012). The present study has added to this view by showing how a Likert-based digital monitoring index can represent the readiness of a water utility to support observation, early warning, response, and continuity. The result has also aligned with the Safe and SuRe approach, where water management resilience has been connected with reliability, resilience, sustainability, and the ability to manage known and uncertain threats (Butler et al., 2017). The findings have further supported operational resilience literature, which has emphasized that infrastructure resilience requires design and analysis of critical functions under disruptive conditions (Ganin et al., 2016). In this study, SCADA-based monitoring has represented the observation and control function, IoT-enabled metering has represented distributed sensing, real-time data quality has represented trustworthy interpretation, predictive analytics has represented early warning, and SCADA-IoT integration has represented coordinated response. The stronger effect of SCADA-IoT integration, $\beta = 0.31$, has shown that resilience has been more dependent on system coordination than on the isolated presence of technology. Therefore, the theoretical implication has been that resilience theory can be operationalized in smart water metering studies through a measurable structure: SMC, ISMC, RTDQ, PAAD, and SII as resilience-building capabilities, and RSM as the resilience outcome. This supports the idea that technology has become theoretically meaningful only when it has strengthened the system's capacity to detect, absorb, respond, and maintain service continuity.

The practical implications of the findings have been important for water utilities, municipal authorities, smart city planners, and infrastructure managers because the results have identified which digital capabilities have contributed most strongly to resilient supply monitoring. The strongest practical message has been that SCADA-IoT integration should be treated as the central priority, because it has recorded the highest descriptive mean of 4.16, the strongest correlation with resilient supply monitoring, $r = 0.69$, and the highest regression effect, $\beta = 0.31$. This means that utilities have gained more monitoring value when supervisory control, smart meter data, dashboards, alerts, and analytical systems have operated as a unified monitoring environment. For water utility managers, this suggests that investments in smart meters or SCADA modernization should not be planned separately. A practical monitoring strategy should include interoperable meter data management, SCADA dashboard integration, pressure and flow sensor connectivity, anomaly detection rules, alarm prioritization, and operator training. The second strongest predictor has been predictive analytics and anomaly detection, $\beta = 0.24$, which means that utilities should develop analytics capacity for leakage identification, pressure deviation monitoring, abnormal-consumption recognition, and district-level early warning. This result has been consistent with studies on machine-learning-based leak detection, where smart monitoring data have been used to identify emergent leaks and anomalies in district-metered areas (Głomb et al., 2023). The practical importance of data quality has also been visible because real-time data quality has had a significant positive effect on resilient supply monitoring, $\beta = 0.15$, $p = 0.005$. Although it has been the smallest predictor in the model, it has remained statistically meaningful because poor data quality can weaken every other monitoring function. Utilities should therefore ensure sensor calibration, meter validation, communication reliability, timestamp consistency, missing-data treatment, cybersecurity, and dashboard accuracy. The high RRI score of 4.02 has shown that the studied case context has had high readiness, but the slightly lower mean for predictive analytics, 3.89, has indicated that analytics maturity may need more practical attention than basic monitoring. Therefore, the findings have offered a practical roadmap: integrate SCADA and IoT first, strengthen analytics second, improve data quality continuously, and use resilience readiness assessment to monitor digital water capability over time.

The limitations revisited through the findings have shown that the study has produced strong evidence, but its interpretation has still been shaped by methodological and contextual boundaries.

First, the study has used a cross-sectional design, which has allowed the researcher to measure relationships among variables at one point in time. This design has been suitable for testing the hypotheses, but it has not measured how SCADA-IoT capability, data quality, analytics maturity, and resilient supply monitoring change across months or years. Second, the study has depended on 214 professional responses collected through a case-study-based survey. Although the sample has been relevant because respondents have included water utility staff, SCADA operators, IoT technicians, water distribution engineers, data analysts, and municipal staff, the results have still reflected professional perceptions rather than direct hydraulic performance records from the water network. Third, the five-point Likert scale has allowed the study to quantify perceptions reliably, as shown by Cronbach's alpha values from 0.82 to 0.90, but Likert-scale data cannot fully capture all technical details of pressure transients, pipe bursts, leakage volume, sensor drift, communication latency, and SCADA alarm logic. Fourth, the study has explained 59.4% of the variance in resilient supply monitoring, which has been strong, but 40.6% of the variance has remained unexplained. This indicates that other factors such as organizational readiness, cybersecurity maturity, budget capacity, staff training, pipe age, maintenance culture, regulatory pressure, and consumer participation may also influence resilience. Fifth, the Resilience Readiness Index has given equal weight to SMC, ISMC, RTDQ, PAAD, and SII. This has been useful for clarity, but the regression results have shown that integration and analytics have had stronger effects than data quality or IoT metering alone. Therefore, future versions of the index may use weighted scores based on regression coefficients. Earlier resilience studies have noted that resilience metrics can vary depending on system type, function, and measurement purpose ([Shin et al., 2018](#)). The present limitation has therefore been consistent with prior resilience measurement debates because no single index can fully represent every operational, hydraulic, cyber-physical, and organizational dimension of water supply resilience. These limitations have not weakened the findings, but they have clarified how the results should be interpreted within the scope of a quantitative, case-study-based design.

Future research should build on the present findings by developing and testing an Integrated SCADA-IoT Water Resilience Maturity Model, which can be abbreviated as ISIW-RMM. This proposed model can improve the present study by adding time-based measurement, operational sensor data, cybersecurity indicators, organizational readiness, and weighted resilience scoring. The first layer of the model should be the Digital Sensing Layer, which measures smart meter coverage, pressure sensor density, flow sensor reliability, communication uptime, and meter data completeness. The second layer should be the Supervisory Control Layer, which measures SCADA alarm quality, pump and valve visibility, operator response time, historical event logging, and control-room decision support. The third layer should be the Data Intelligence Layer, which measures real-time data quality, missing-data rates, anomaly detection accuracy, false alarm reduction, leak detection speed, and predictive model performance. The fourth layer should be the Integration and Cyber-Physical Security Layer, which measures SCADA-IoT interoperability, dashboard integration, API connectivity, cybersecurity monitoring, access control, and protection against false data or communication disruption. The fifth layer should be the Resilience Performance Layer, which measures supply continuity, pressure recovery, leakage response time, abnormal-consumption resolution, downtime reduction, and customer service reliability. In mathematical form, future researchers can improve the current RRI formula by using weighted coefficients derived from regression or structural equation modeling: , where refers to Weighted Resilience Readiness Index, refers to cybersecurity maturity, and refers to organizational readiness maturity. This proposed model would improve the present study because it would move from equal-weight readiness scoring to evidence-weighted resilience maturity assessment. Future research can also use longitudinal data to examine whether readiness improves after SCADA-IoT upgrades, smart meter expansion, analytics implementation, or staff training. A mixed-method design can also be used by combining survey data with SCADA logs, smart meter records, pressure datasets, leak repair records, and expert interviews. This direction has aligned with digital water transformation research, where water utilities have been shown to differ in drivers, impacts, and enabling technologies across countries and organizational contexts ([Daniel et al., 2023](#)). It has also aligned with smart water framework research, which has emphasized the need for structured system-level thinking in smart water development ([Li et al., 2020](#)). Therefore, the proposed ISIW-RMM

can serve as a future research model for improving this study by connecting digital maturity, operational performance, cybersecurity, organizational readiness, and resilience outcomes in one advanced framework.

CONCLUSION

This study has concluded that SCADA and IoT-enabled smart water metering have played a significant role in strengthening resilient supply monitoring in the selected water utility and smart water management context. The research has been conducted through a quantitative, cross-sectional, case-study-based design using a five-point Likert scale, descriptive statistics, reliability analysis, correlation analysis, regression modeling, and a resilience readiness index. The findings have shown that all major constructs have received high agreement from the respondents, indicating that professionals have recognized the value of digital monitoring capabilities in improving water supply visibility, fault detection, data-based decision-making, and service continuity. SCADA-IoT integration has recorded the highest mean score of 4.16, followed by resilient supply monitoring at 4.11, SCADA-based monitoring capability at 4.08, IoT-enabled smart metering capability at 4.02, real-time data quality at 3.96, and predictive analytics and anomaly detection at 3.89. These results have indicated that integrated digital monitoring has been perceived as the strongest factor in improving supply resilience. The reliability analysis has confirmed the internal consistency of the measurement constructs, with Cronbach's alpha values ranging from 0.82 to 0.90 and an overall scale reliability of 0.92. The correlation findings have shown that all independent variables have had positive and significant relationships with resilient supply monitoring, with SCADA-IoT integration showing the strongest relationship at $r = 0.69$. The regression model has further confirmed the explanatory strength of the study framework, as the five predictors have explained 59.4% of the variance in resilient supply monitoring, with $R^2 = 0.594$ and adjusted $R^2 = 0.584$. All five hypotheses have been supported, showing that SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, and SCADA-IoT integration have had significant positive effects on resilient supply monitoring. The additional operational result on leakage, pressure, and abnormal-consumption detection performance has produced a high mean score of 4.07, which has shown that SCADA and IoT-enabled systems have been practically useful for identifying abnormal water consumption, leakage-prone zones, pressure faults, and delayed supply-fault conditions. The Resilience Readiness Index has produced an overall score of 4.02 out of 5.00, placing the case context within the high readiness category. Therefore, the study has proved its objectives by showing that resilient supply monitoring has depended on a connected set of digital monitoring capabilities rather than on isolated technology adoption. From the perspective of resilience theory, the findings have shown that SCADA has supported observation and control, IoT smart metering has supported distributed sensing, data quality has supported reliable interpretation, predictive analytics has supported early warning, and system integration has supported coordinated response in smart water supply monitoring.

RECOMMENDATIONS

This study has recommended that water utilities, municipal authorities, infrastructure managers, and smart city planners should prioritize the integration of SCADA and IoT-enabled smart water metering as a central strategy for strengthening resilient supply monitoring. Since SCADA-IoT integration has recorded the highest descriptive mean of 4.16 and the strongest regression effect of $\beta = 0.31$, utilities should not treat SCADA modernization and smart meter deployment as separate projects. Instead, they should design one connected monitoring architecture where SCADA dashboards, IoT smart meters, pressure sensors, flow meters, alarm systems, meter data platforms, and predictive analytics tools can exchange information in a coordinated way. Water utilities should also improve real-time data quality because data accuracy, timeliness, completeness, consistency, and reliability have been found to significantly influence resilient supply monitoring. This means that utilities should regularly calibrate sensors, validate meter readings, reduce missing data, maintain communication networks, standardize time-stamped records, and establish data-cleaning procedures before using the data for operational decisions. Predictive analytics and anomaly detection should also receive stronger attention because this construct has shown the second strongest regression effect, $\beta = 0.24$. Utilities should develop analytical models for leakage detection, pressure deviation identification, abnormal-consumption recognition, meter tampering alerts, and district-level early warning. Since the mean score for

predictive analytics has been 3.89, which is high but slightly lower than the other major constructs, this area should be improved through staff training, software investment, data science collaboration, and pilot testing of machine learning or rule-based detection models. Water utilities should also use the Resilience Readiness Index as an internal assessment tool to evaluate whether their SCADA capability, IoT metering capability, real-time data quality, predictive analytics, and system integration are improving over time. The RRI score of 4.02 has indicated high readiness in this study, but utilities can use the same formula to compare departments, zones, districts, or implementation stages. Another recommendation is that water utilities should train operators, engineers, and monitoring staff to interpret integrated dashboard information rather than only respond to basic alarms. Operator training should focus on pressure behavior, leakage indicators, abnormal consumption patterns, data-quality warnings, and response prioritization. Municipal authorities should also support investment in smart water infrastructure through policy, budget allocation, cybersecurity standards, and digital water governance. Finally, future implementation should include cybersecurity protection because SCADA and IoT-enabled systems are cyber-physical infrastructures. Access control, network segmentation, authentication, data backup, and cyber incident response should be included in smart water monitoring plans so that digital resilience and operational resilience can work together.

LIMITATIONS OF THE STUDY

This study has had several limitations that should be considered when interpreting the findings. First, the research has used a quantitative, cross-sectional design, which means that data have been collected at one point in time. This design has been suitable for measuring the relationships among SCADA-based monitoring capability, IoT-enabled smart metering capability, real-time data quality, predictive analytics and anomaly detection, SCADA-IoT integration, and resilient supply monitoring, but it has not captured how these relationships may change over time. Smart water systems often develop gradually through technology upgrades, sensor expansion, staff training, data-quality improvement, and dashboard integration, so a longitudinal design could provide a deeper understanding of maturity and performance change. Second, the study has depended on perception-based survey responses from 214 professionals. Although the respondents have been relevant because they have included water utility staff, SCADA operators, IoT technicians, water distribution engineers, data analysts, and municipal authority personnel, the findings have still reflected professional judgment rather than direct operational measurements from SCADA logs, smart meter datasets, pressure records, leakage repair reports, or flow-monitoring systems. Third, the study has used a five-point Likert scale, which has helped quantify the respondents' agreement with each construct, but this method may not fully capture the technical complexity of water supply monitoring. Issues such as pressure transients, burst magnitude, leakage duration, sensor drift, communication latency, false alarm rates, cybersecurity events, and hydraulic model accuracy may require technical datasets beyond survey responses. Fourth, the study has focused on a case-study-based context, which has strengthened practical relevance but may limit the generalizability of the findings to all water utilities, especially those with different infrastructure conditions, financial capacity, SCADA maturity, IoT coverage, regulatory requirements, and climate-related pressures. Fifth, the regression model has explained 59.4% of the variance in resilient supply monitoring, which has shown strong explanatory power, but 40.6% of the variance has remained unexplained. This indicates that other factors may also influence resilience, including organizational readiness, staff capability, maintenance culture, funding availability, pipe age, cybersecurity maturity, consumer participation, and emergency management capacity. Sixth, the Resilience Readiness Index has used equal weighting for SCADA capability, IoT metering capability, real-time data quality, predictive analytics, and SCADA-IoT integration. This approach has made the index simple and interpretable, but the regression findings have shown that all constructs do not have equal statistical influence. SCADA-IoT integration and predictive analytics have had stronger effects than real-time data quality and IoT-enabled metering alone. Therefore, a future version of the index could apply weighted coefficients based on regression, structural equation modeling, or expert judgment. These limitations have not reduced the value of the study, but they have clarified the methodological boundaries within which the findings should be understood.

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