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Full Length Research Paper

Sustainability of Urban Water Service Delivery: Integrating Policy, Partnerships, and Smart Water Metering in Dodoma City, Tanzania

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Abstract

This paper presents a GIS-based engineering assessment of the association between smart water metering, Non-Revenue Water (NRW), and Revenue Collection Efficiency (RCE) in Dodoma City, Tanzania. The analysis combined utility-level time-series data for 2021–2025, GIS-based spatial analysis of ward-level prepaid meter distribution, and household-level econometric analysis involving 384 respondents. Results showed that smart meter coverage increased from 16.9% in 2021 to 26.8% in 2023 before declining to 10.1% in 2025. NRW showed a strong negative association with smart meter coverage for 2021–2024 ($r = -0.72$), while RCE showed a moderate positive association ($r = +0.58$). Spatial analysis indicated uneven meter deployment across wards, with smart meter density positively associated with connection rates ($r = +0.62$), billing accuracy ($r = +0.38$), and user satisfaction ($r = +0.35$), and negatively associated with reported NRW experience ($r = -0.41$). Logistic regression showed that households using prepaid meters had lower odds of reporting water-loss experience than conventional meter users (OR = 0.71, $p = 0.042$). The findings suggest that smart water metering is associated with improved technical and financial performance indicators, although these relationships remain correlational and are influenced by spatial inequality, operational continuity, and system-level management factors. The study highlights the need for equitable deployment, sustained maintenance, and stronger data-driven utility management.

Keywords: Smart water metering; non-revenue water; GIS modelling; revenue collection efficiency; spatial equity

1. Introduction

Non-Revenue Water (NRW) remains a major challenge for urban water utilities worldwide. The problem is more severe in developing countries, where water losses often exceed 35% of the system input volume, compared with generally lower levels in high-income countries (Kingdom, Liemberger, & Marin, 2006). Revenue Collection Efficiency (RCE), defined as the ratio of revenue collected to revenue billed, is also a critical financial indicator for water utilities. In many Sub-Saharan African utilities, weak revenue collection reduces financial viability, limits infrastructure investment, and contributes to declining service quality (GIZ, 2020). The combined pressure of high NRW and low RCE creates a cycle of operational inefficiency, financial stress, and limited network expansion (Global Water Partnership, 2020).

Smart water meters, particularly prepaid and digitally operated meters, are increasingly used to support water-use monitoring, billing management, leakage identification, and customer-account control. When

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combined with Geographic Information Systems (GIS), metering data can help utilities identify spatial patterns of water consumption, billing performance, service coverage, and possible water-loss hotspots (Behailu, Pietilä, & Katko, 2016). However, smart metering should not be treated as a stand-alone solution. Its relationship with NRW and revenue performance depends on maintenance capacity, data quality, customer compliance, institutional follow-up, and wider network-management conditions.

In Tanzania, urban water utilities continue to experience technical and financial performance challenges. NRW levels in many utilities remain above recommended efficiency thresholds, while revenue collection performance varies across systems (Ministry of Water, United Republic of Tanzania, 2022a). The Dar es Salaam Water Supply and Sanitation Authority, for example, has reported NRW levels ranging between 35% and 40%, indicating persistent system inefficiencies (EWURA, 2022). Although prepaid and digital metering initiatives have been introduced in some Tanzanian urban areas, systematic evidence on their association with NRW, billing accuracy, and revenue collection remains limited (Mnyanyi, 2021).

Dodoma City provides an important case for examining these relationships because it is Tanzania's administrative capital and one of the country's rapidly growing urban centres. Population growth and urban expansion have increased pressure on the Makutupora aquifer, which is the city's main groundwater source (Nkotagu, 2011; National Bureau of Statistics, 2022). The Dodoma Urban Water Supply and Sanitation Authority (DUWASA) has introduced prepaid meters as part of efforts to improve service management and revenue performance. However, the extent to which prepaid meter distribution is associated with NRW, RCE, billing accuracy, customer satisfaction, and spatial equity has not been adequately examined using integrated engineering, GIS, and household-level evidence.

Existing studies have not sufficiently combined utility-level performance trends, GIS-based spatial assessment of meter deployment, and household-level econometric analysis in the Tanzanian context. This study addresses that gap by assessing the association between smart water metering, NRW, and revenue collection performance in Dodoma City. Specifically, it analyses utility-level trends for 2021–2025, maps ward-level prepaid meter distribution, and examines household-level relationships between meter type, reported water-loss experience, billing accuracy, and satisfaction. The study provides an evidence base for improving data-driven utility management, strengthening operational efficiency, and supporting more equitable deployment of water-metering technologies.

Although previous studies have examined water utility performance, Non-Revenue Water (NRW), digital metering, and urban water-service challenges in Tanzania, most have treated these issues separately. Limited empirical work has integrated policy frameworks, institutional partnerships, smart water metering, utility-level performance records, GIS-based spatial analysis, and household-level econometric evidence within a single study. This paper contributes by providing an integrated assessment of how smart water metering, policy implementation, and institutional arrangements are associated with technical, financial, customer-related, and spatial equity outcomes in Dodoma City. It further contributes one of the first ward-level assessments of smart meter distribution and service-related equity patterns in the Dodoma urban water system.

1.1 Conceptual Basis of the Study

This study is informed by a socio-technical perspective, which views urban water-service performance as the result of interaction between technology, institutional arrangements, and governance conditions. From this perspective, smart water metering is not treated as a stand-alone solution, but as a technological component whose usefulness depends on maintenance capacity, data quality, policy implementation, institutional coordination, and user compliance.

Accordingly, the study considers sustainable urban water-service delivery as being influenced by three interconnected dimensions: policy and regulatory frameworks, institutional partnerships, and smart water metering. Policy and regulatory frameworks provide performance expectations and accountability mechanisms for utilities. Institutional partnerships support resource mobilisation, technical assistance, information sharing, and coordinated implementation. Smart water metering provides operational data that can support monitoring of consumption, billing performance, and water-loss patterns.

These dimensions are examined in relation to key utility-performance outcomes, including Non-Revenue Water (NRW), Revenue Collection Efficiency (RCE), billing accuracy, customer satisfaction, and spatial equity. The study therefore focuses on identifying statistical and spatial associations among these variables rather than establishing direct causal relationships.

2. Materials and Methods

2.1 Study Area

The study was conducted in Dodoma City, central Tanzania, located approximately at 6°10′S and 35°44′E, with an elevation of about 1,120 m above sea level. Dodoma is the administrative capital of Tanzania and has experienced rapid population growth and urban expansion over the past decade. The city has a semi-arid climate, receiving approximately 500–600 mm of

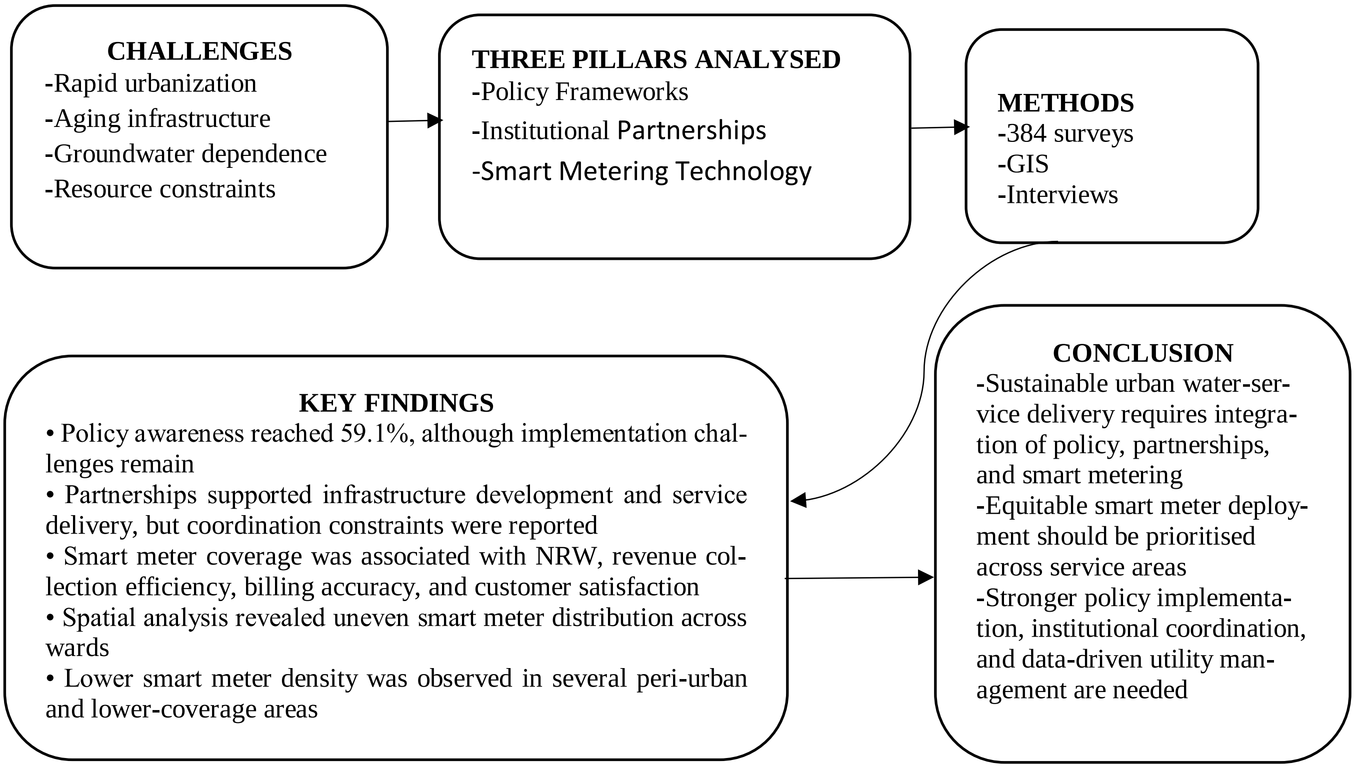

Figure 1: Graphical abstract.

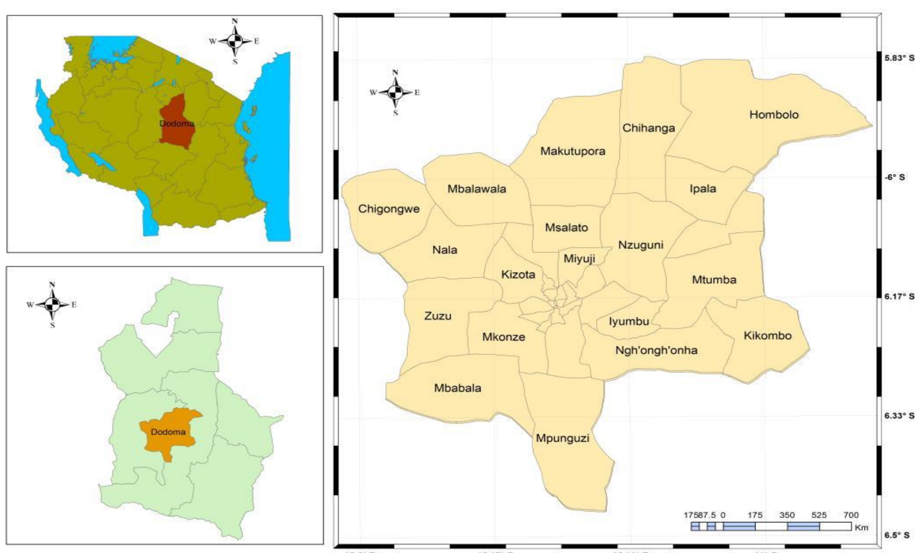

Figure 2: Map of Dodoma City showing Wards.

rainfall annually, and depends mainly on groundwater from the Makutupora aquifer, which is slowly recharged and vulnerable to increasing abstraction pressure (Nkotagu, 2011; DUWASA, 2023). Between 2012 and 2022, the population of Dodoma increased from 410,956 to 765,179, intensifying demand for urban water services (National Bureau of Statistics, 2022). The Dodoma Urban Water Supply and Sanitation Authority (DUWASA) manages water supply and sanitation services in the city. Although overall service coverage is estimated at about 78%, coverage differs across wards, creating spatial variation in access, connection density, and metering distribution (DUWASA, 2023).

2.2 Research Design

The study adopted a quantitative multi-level analytical design integrating three components: utility-level time-series analysis, GIS-based spatial analysis, and household-level econometric analysis. Utility performance data for 2021–2025 were used to examine trends in Non-Revenue Water (NRW), Revenue Collection Efficiency (RCE), and smart meter coverage. GIS analysis was used to assess the spatial distribution of prepaid meters across wards, while household survey data from 384 respondents were used to examine associations between meter type, reported water-loss experience, billing accuracy, and customer satisfaction. This design allowed the study to compare system-level performance trends with spatial and household-level patterns. However, because the study was observational and relied on short time-series data, the findings are interpreted as associations rather than causal effects.

2.3 Study Population

The study population comprised residential households within Dodoma City served under different water-service coverage conditions. Households were selected from high-, medium-, and low-coverage areas to capture variation in connection status, metering type, reported water-loss experience, billing accuracy, and customer satisfaction.

Institutional stakeholders, including DUWASA officials, regulatory actors, local government representatives, and water-sector partners, were included as key informants to provide contextual information on policy implementation, institutional coordination, partnership effectiveness, and smart metering operations. Their responses were used to support interpretation of the quantitative and spatial findings.

2.4 Sampling Procedure and Sample Size

A stratified random sampling technique was employed to select household respondents. The study area was divided into three strata based on the level of water-service coverage: high-coverage, medium-coverage, and low-coverage areas. Households were proportionally selected from each stratum to ensure adequate representation of differences in water connection status, meter type, service reliability, billing accuracy, reported water-loss experience, and customer satisfaction.

The minimum household sample size was determined using Cochran's formula for a large population, which is expressed as:

$$n_0 = \frac{Z^2 p(1-p)}{e^2}$$

Where:

- n_0 = required minimum sample size
- Z = standard normal value corresponding to the selected confidence level
- p = estimated proportion of the population possessing the characteristic of interest
- e = acceptable margin of error

A 95% confidence level was adopted, corresponding to $Z = 1.96$. Since the actual population proportion was unknown, $p = 0.5$ was used to provide the maximum possible sample size (i.e., the most conservative estimate). The margin of error was set at 5% ($e = 0.05$). Substituting these values into Cochran's formula:

$$n_0 = \frac{(1.96)^2(0.5)(1-0.5)}{(0.05)^2}$$

$$n_0 = \frac{3.8416 \times 0.25}{0.0025} = \frac{0.9604}{0.0025} = 384.16$$

The calculated value was rounded up to a minimum sample of 384 households.

To compensate for potential non-response, incomplete questionnaires, and data-quality problems, 420 questionnaires were distributed. Of these, 408 questionnaires were returned, giving a questionnaire return rate of 97.1%. Following data screening and cleaning, 24 returned questionnaires were excluded because they were incomplete or contained inconsistent responses. Consequently, 384 valid questionnaires were retained for statistical analysis. This represented a valid response rate of 91.4% of all questionnaires distributed and a validity rate of 94.1% among the returned questionnaires.

Key informants were selected purposively from the Dodoma Urban Water Supply and Sanitation Authority (DUWASA), regulatory institutions, local government authorities, and water-sector partner organisations. These participants were selected based on their institutional responsibilities, professional knowledge, and direct involvement in water-policy implementation, institutional coordination, partnership arrangements, and smart water-metering operations.

2.5 Data Collection Methods

Data were collected from primary and secondary sources. Primary data were collected through structured household questionnaires and key informant interviews. The household questionnaire captured information on water-service access, connection status, metering type, reported water-loss experience, billing accuracy, customer satisfaction, and awareness of water policies.

Key informant interviews were conducted with DUWASA officials, regulatory actors, local government representatives, and water-sector partners. The interviews focused on policy implementation, institutional coordination, partnership arrangements, operational challenges, and smart metering practices.

Secondary data were obtained through documentary review of national water policies, DUWASA operational records, utility performance reports, financial records, smart meter coverage data, and NRW-related reports. These sources were used to triangulate household survey findings, GIS-based spatial analysis, and institutional information.

2.6 Data Analysis

Survey data were coded and analysed using SPSS v27 and R v4.3. Descriptive statistics, including frequencies, percentages, means, and standard deviations, were used to summarise respondent characteristics and key study variables. Chi-square tests were applied to examine associations between categorical variables, including policy awareness, connection status, and service-coverage category. Statistical significance was assessed at the 5% level ($p < 0.05$).

Non-Revenue Water (NRW) and Revenue Collection Efficiency (RCE) were computed using standard utility performance indicators. NRW was calculated as:

$$NRW_t = \frac{System\ Input_t - Billed\ Consumption_t}{System\ Input_t} \times 100 \qquad (1)$$

where System Input Volume refers to the total volume of water entering the distribution system, and Billed Authorized Consumption refers to the volume of water billed to customers.

$$RCE_t = \frac{Revenue\ Collected_t}{Revenue\ Billed_t} \times 100 \qquad (2)$$

where Revenue Collected refers to the actual revenue received by the utility, and Revenue Billed refers to the total amount billed to customers. This definition of RCE was applied consistently throughout the analysis.

Pearson correlation analysis was used to examine associations between smart meter coverage, NRW, and RCE over the study period. At ward level, smart meter density was correlated with connection rate, billing accuracy, customer satisfaction, and reported NRW experience. These analyses were interpreted as associative because the study used observational data and a short time-series period.

GIS analysis was conducted using QGIS 3.28 in UTM Zone 36S. Prepaid meter coordinates were mapped, cleaned, validated, and aggregated at ward level to determine smart meter density. Ward-level density was calculated as the number of prepaid meters per square kilometre. The study did not conduct spatial autocorrelation or hotspot modelling; instead, it used descriptive ward-level spatial comparison to assess variation in smart meter deployment and service-related indicators.

Household-level analysis was conducted using logistic and linear regression models. Logistic regression was used to examine the association between meter type and reported water-loss experience, controlling for coverage category, connection status, household size, and education level. Linear regression was used to assess the association between meter type and perceived billing accuracy while accounting for socio-demographic factors.

Qualitative interview data and policy documents were analysed using thematic content analysis. Interview responses were coded around policy implementation, NRW reduction, pro-poor service expansion, tariff and billing reliability, institutional coordination, and smart metering operations. Relevant provisions from NAWAPO 2022 and the Water Supply and Sanitation Act No. 5 of 2019 were reviewed to interpret policy implementation gaps.

3. Results

3.1 Socio-Demographic Profile of Respondents

A total of 384 valid household responses were analysed, representing a response rate of 91.4%. The sample was nearly balanced by gender, with females accounting for 51.3% and males 48.7%. Most respondents were economically active, with 61.2% aged between 31 and 60 years. Connected households accounted for 78.4% of the sample, while 21.6% were not connected to the utility network. The mean household size was 5.1 ± 2.3 members, as shown in Table 1.

3.2 Water Policy and Regulatory Frameworks

3.2.1 Policy Awareness

Overall, 59.1% of respondents reported awareness of water-related policies and regulations. Policy awareness varied by coverage category and connection status. Respondents in high-coverage wards reported higher awareness than those in medium- and low-coverage wards. Similarly, connected households reported higher awareness than unconnected households. Connection status was significantly associated with policy awareness ($\chi^2 = 12.65$, $p < 0.001$), as shown in Table 2.

3.2.2 Perceived Policy Implementation

Respondents expressed mixed views on policy implementation. Approximately 49.4% considered water policies effective or very effective, while 26.8% considered them ineffective or very ineffective. The remaining 23.7% were neutral. Perceived policy effectiveness differed significantly across coverage groups ($\chi^2 = 12.48$, $p = 0.002$), indicating that households in better-served areas were more likely to perceive water policies positively.

Table 1: Socio-demographic characteristics of survey respondents (N = 384).

Characteristic	Category	Frequency	Percentage (%)
Gender	Male	187	48.7
	Female	197	51.3
Age	18–30	118	30.7
	31–45	147	38.3
	46–60	88	22.9
	>60	31	8.1
Education	None	42	10.9
	Primary	141	36.7
	Secondary	123	32.0
	Diploma	51	13.3
	Degree+	27	7.0
Connection	Connected	301	78.4
	Not connected	83	21.6

Table 2: Policy awareness by coverage category and connection status.

Variable	Category	Aware (%)	Not aware (%)
Coverage	High	67.2	32.8
	Medium	58.6	41.4
	Low	49.2	50.8
Connection	Connected	63.8	36.2
	Not connected	42.2	57.8

3.2.3 Policy Contribution to Sustainability

A slight majority of respondents (52.9%) indicated that water policies made a positive or very positive contribution to service sustainability. However, positive perceptions declined from high-coverage wards (60.9%) to low-coverage wards (44.5%), and this difference was statistically significant ($\chi^2 = 6.62$, $p = 0.036$). This pattern suggests that policy benefits were perceived unevenly across service areas.

Key informant evidence supported this interpretation. One respondent stated:

“Water policy is clear at national level, but coordination delays occur, especially under rapid urban growth pressures” (KI-17)

This indicates that the main challenge is not only policy awareness, but also implementation capacity, institutional coordination, and translation of national policy objectives into service improvements at ward level.

In relation to NAWAPO 2022 (Ministry of Water, United Republic of Tanzania, 2022b) and the Water Supply and Sanitation Act No. 5 of 2019 (United Republic of Tanzania, 2019), the results suggest implementation gaps in three areas: NRW reduction, equitable service expansion, and tariff and billing reliability.

3.3 Partnerships in the Water Sector

3.3.1 Partnership Structure

Water-sector partnerships in Dodoma involved several actors, including central government institutions, the Energy and Water Utilities Regulatory Authority (EWURA), local government, development partners, private-sector contractors, non-governmental organisations (NGOs), and community-based organisations (CBOs), as shown in Table 3.

3.3.2 Partnership Effectiveness

Partnerships were reported to support infrastructure development, regulatory compliance, technical assistance, and public engagement. However, key informant responses indicated that weak coordination and uneven community participation limited the effectiveness of some partnership arrangements.

Participation in water-related meetings was positively associated with service satisfaction ($r = 0.312$, $p < 0.001$; $r^2 \approx 0.097$). This indicates that households involved in water-related engagement activities tended to report higher satisfaction, although the association was modest and should not be interpreted causally.

Key informant evidence supported this interpretation. One respondent stated:

“Partnerships help, but the pace at which infrastructure is needed exceeds the speed of capacity expansion” (KI-28).

This suggests that partnerships contribute to service improvement but are constrained by rapid urban growth, infrastructure demand, and institutional coordination challenges.

3.4 Smart Water Metering and Utility Performance

3.4.1 System Performance, 2021–2025

Non-Revenue Water (NRW) and Revenue Collection Efficiency (RCE) were analysed to assess technical and financial performance during the study period. NRW remained high, ranging from 33.1% to 43.9%. NRW increased from 35.8% in 2021 to 39.0% in 2022, declined to 33.1% in 2024, and then rose sharply to 43.9% in 2025.

RCE was interpreted as the proportion of billed revenue successfully collected by the utility. RCE increased from 80.0% in 2021 to 91.8% in 2024 before declining to 86.7% in 2025. The lowest NRW value and highest RCE value both occurred in 2024, suggesting a possible association between technical and financial performance. However, the reversal observed in 2025 shows that this relationship was not consistent across the full study period.

3.4.2 Smart Meter Coverage

Smart meter coverage increased from 16.9% in 2021 to 26.8% in 2023, before declining to 20.0% in 2024 and 10.1% in 2025. The sharp decline in 2025 coincided with the highest NRW value recorded during the study period. This anomaly may reflect operational instability, delayed replacement of faulty meters, incomplete updating of meter records, data-quality limitations, or external pressure on the water supply system. Therefore, the 2025 results should be interpreted cautiously and treated as requiring further operational verification.

3.4.3 Time-Series Correlations

The correlation between smart meter coverage and NRW was strong and negative for 2021–2024 ($r = -0.72$), indicating that higher smart meter coverage was associated with lower NRW during this period. However, when the 2025 data point was included, the association weakened to $r = -0.31$, showing that the relationship was sensitive to the 2025 anomaly.

Smart meter coverage also showed a moderate positive association with RCE for 2021–2025 ($r = +0.58$), suggesting that higher smart meter coverage coincided with stronger revenue collection performance. These results should, however, be interpreted as correlational evidence rather than proof that smart metering directly reduced NRW or improved RCE.

3.4.4 GIS-Based Spatial Smart Meter Density

Ward-level smart meter density was calculated by dividing the number of prepaid meters in each ward by the ward area in square kilometres. Spatial analysis showed that smart meter distribution was uneven across Dodoma City, with higher concentrations in high-

Table 3: Key water-sector partnerships.

Partner	Key actors	Contribution
Central government	Ministry of Water	Policy oversight, coordination
Regulator	EWURA	Compliance monitoring
Local government	Dodoma City Council	Infrastructure planning, community liaison
Development partners	Donor agencies	Technical assistance, investment
Private sector	Contractors/firms	Specialized expertise, project execution
Civil society/NGOs	CBOs	Public engagement, education

Table 4: Annual NRW and RCE.

Year	Input (m^3/day)	Billed (m^3/day)	NRW (%)	RCE (%)
2021	102,156	68,934	35.8	80.0
2022	96,156	65,826	39.0	82.6
2023	111,046	62,472	34.6	81.4
2024	113,381	68,990	33.1	91.8
2025	106,959	70,165	43.9	86.7

coverage and more central wards, while peri-urban and lower-coverage wards had relatively fewer prepaid meters.

To strengthen the spatial equity assessment, ward-level smart meter density was compared with connection rate, reported NRW experience, billing accuracy, and overall satisfaction. The results showed that smart meter density was positively associated with connection rate ($r = +0.62$), billing accuracy score ($r = +0.38$), and overall satisfaction ($r = +0.35$), but negatively associated with reported NRW experience ($r = −0.41$), as shown in Table 6.

To further assess equity, smart meter density was interpreted alongside service-coverage category and connection-related indicators. Service coverage was used as the main equity stratifier because the survey was designed around high-, medium-, and low-coverage areas. The results indicate that smart meter density was higher in better-served wards and lower in peri-urban and low-coverage areas, suggesting unequal access to metering-related service benefits.

These results suggest that wards with higher smart meter density also tended to have stronger service-related indicators. However, this pattern also raises a spatial equity concern because lower-coverage wards may have fewer opportunities to benefit from metering-related service improvements, billing reliability, and utility monitoring. Therefore, future smart meter expansion should prioritise under-served wards to avoid reinforcing existing service disparities. Figure 3 presents the spatial distribution of smart meter density across Dodoma City, illustrating variation in deployment intensity across administrative wards.

3.4.5 Household-Level Econometric Analysis

Logistic regression analysis was conducted to examine the association between meter type and reported NRW experience while controlling for connection status, coverage category, education level, and household size. The results showed that households using prepaid meters had lower odds of reporting NRW experience

Table 5: Smart meter coverage, 2021–2025.

Year	Smart meter coverage (%)
2021	16.9
2022	19.6
2023	26.8
2024	20.0
2025	10.1

Table 6: Ward-level smart meter density and service indicators.

Performance indicator	Correlation with smart meter density
Connection rate	+0.62
Reported NRW experience	−0.41
Billing accuracy score	+0.38
Overall satisfaction	+0.35

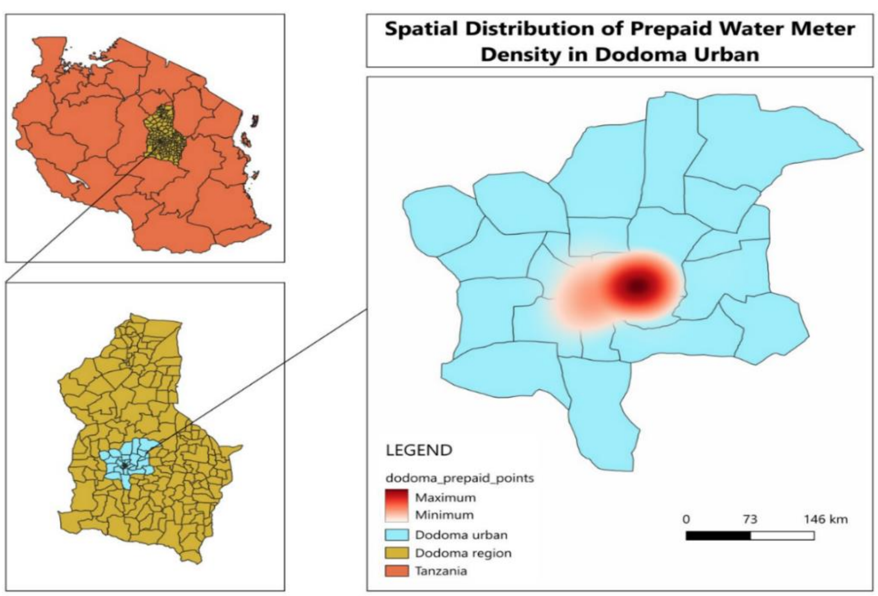

Figure 3: Spatial distribution of smart water meter density in Dodoma City.

Source: DUWASA prepaid meter coordinate data and author's GIS processing. The map shows ward-level variation in prepaid meter density and includes legend, scale bar, north arrow, and location inset.

Table 7: Logistic regression results for determinants of reported NRW experience.

Variable	OR	p-value	95% CI
Prepaid meter	0.71	0.042	0.51–0.99
Connected	0.58	0.008	0.39–0.86
High-coverage ward	0.63	0.021	0.43–0.93
Education	0.82	0.156	0.62–1.08
Household size >5	1.24	0.091	0.97–1.59

Table 8: Linear regression results for determinants of billing accuracy perception.

Variable	Coefficient	p-value
Prepaid meter	+0.47	<0.001
High-coverage ward	+0.29	0.018
Household size	−0.05	0.221
Education	+0.12	0.104

than households using conventional meters (OR = 0.71, p = 0.042). Similarly, connected households and households located in high-coverage wards were less likely to report NRW experience. Education level and household size were not statistically significant predictors.

Linear regression analysis was conducted to examine the association between prepaid meter use and perceived billing accuracy. The results showed a positive and statistically significant association between prepaid meter use and billing accuracy perception (β = +0.47, $p < 0.001$). Households located in high-coverage wards also reported higher billing accuracy perceptions, while education level and household size were not statistically significant predictors.

These findings indicate that prepaid meter use was associated with reported NRW experience and billing accuracy perception. However, because the study was observational, the results should not be interpreted as evidence of direct causal effects.

3.5 Key Findings Summary

Table 9 summarises the principal findings of the study across the three thematic dimensions of policy frameworks, institutional partnerships, and smart water metering.

The findings indicate that policy awareness, institutional partnerships, and smart water metering were associated with differences in technical, financial, and customer-related performance indicators.

4.0 Discussion

The findings demonstrate that sustainable urban water-service delivery in Dodoma City is associated with the interaction of smart water-metering technology, policy implementation and institutional partnerships. Smart meter coverage was associated with technical, financial, spatial and customer-related indicators, including Non-Revenue Water (NRW), Revenue Collection Efficiency (RCE), billing accuracy and customer satisfaction. However, the study used observational data, a short utility-level time series and cross-sectional household information. The reported relationships should therefore be interpreted as statistical associations rather than evidence of direct causal effects.

During 2021–2024, smart meter coverage showed a strong negative association with NRW, with a correlation coefficient of ($r=-0.72$). This indicates that years with

Table 9: Summary of key findings by study objective.

Objective	Key finding	Statistical evidence
Policy frameworks	Policy awareness was 59.1%, with significant variation by connection status and service coverage level	$\chi^2 = 12.65$, $p < 0.001$
Institutional partnerships	Participation in water-related meetings was positively associated with service satisfaction	$r = 0.312$, $p < 0.001$
Smart water metering	Smart meter coverage was negatively associated with NRW and positively associated with RCE. Prepaid meter use was associated with lower odds of reported NRW experience and higher perceived billing accuracy	$r = -0.72$ (2021–2024); $r = +0.58$ (RCE); OR = 0.71; $\beta = +0.47$

relatively higher smart meter coverage tended to record lower NRW levels. The result is consistent with previous studies indicating that advanced metering systems may support improved consumption measurement, detection of abnormal water use, reduction of unbilled consumption and greater billing accountability (Giné-Garriga et al., 2019). Nevertheless, smart meters cannot independently address every component of NRW. Real losses caused by pipe leakage, bursts, reservoir overflows and ageing infrastructure require network rehabilitation, pressure management, active leakage control and timely maintenance. Metering technologies are more directly related to the management of apparent losses, such as inaccurate measurement, unauthorised consumption and weaknesses in customer-account records.

The 2025 observation differed markedly from the pattern recorded during 2021–2024. Smart meter coverage declined to 10.1%, while NRW increased to 43.9%, the highest level observed during the study period. A sensitivity comparison showed that the correlation between smart meter coverage and NRW weakened from ($r=-0.72$) for 2021–2024 to ($r=-0.31$) when the 2025 observation was included. This substantial change demonstrates that the estimated relationship was highly sensitive to the 2025 data point and should not be interpreted without considering the short time series.

The unusual 2025 pattern may be associated with operational instability, delays in replacing faulty meters, incomplete updating of meter records, changes in the classification of operational meters, data-quality limitations or broader pressure on the urban water-supply system. These explanations cannot be confirmed using the available dataset and should therefore be treated as plausible hypotheses rather than established causes. Verification would require detailed analysis of DUWASA's meter-installation records, faulty-meter registers, replacement schedules, water-production records, billing databases, network-maintenance reports and annual operational changes. The finding reinforces the need to maintain consistent definitions and reporting procedures when calculating annual smart meter coverage and NRW.

The positive association between smart meter coverage and RCE further suggests that digital and prepaid metering may support utility financial performance. Smart meter coverage was moderately positively associated with RCE during 2021–2025 (($r=+0.58$)). This means that years with higher smart meter coverage generally coincided with stronger revenue-collection performance. Prepaid meters may reduce billing delays, limit accumulation of unpaid accounts and strengthen the relationship between water consumption and payment. However, the association was not perfectly consistent, as shown by the decline in RCE from 91.8% in 2024 to 86.7% in 2025. Revenue collection is influenced not only by meter technology but also by tariff administration, customer affordability, billing-system reliability, database management, complaint resolution and enforcement of payment procedures. Smart metering should therefore be viewed as one component of a broader financial-management system.

The GIS-based findings revealed substantial spatial differences in smart meter deployment across Dodoma City. Higher smart meter densities were generally observed in central and high-coverage wards, whereas peri-urban and low-coverage areas had fewer prepaid meters. Smart meter density was positively associated with connection rate (($r=+0.62$)), billing accuracy (($r=+0.38$)) and customer satisfaction (($r=+0.35$)), while it was negatively associated with reported NRW experience (($r=-0.41$)). These patterns indicate that wards with greater meter deployment also tended to report stronger service-related outcomes.

However, the spatial findings also raise an important equity concern. Concentrating smart meters in already better-served areas may reinforce existing differences in service access, billing reliability and utility monitoring. Similar urban infrastructure patterns have been reported where investment tends to favour areas with higher connection density, greater accessibility or stronger revenue potential (Pérez, 2020). In Dodoma, peri-urban and low-coverage wards may consequently have fewer opportunities to benefit from improved consumption monitoring, billing accuracy and customer-service management. Future meter-deployment programmes should therefore use service coverage and infrastructure deprivation as allocation criteria rather than relying primarily on existing connection density or revenue potential.

The spatial-equity interpretation should nevertheless remain cautious because the analysis did not incorporate ward-level income, poverty or household-expenditure data. The observed distribution of smart meters demonstrates spatial inequality in deployment but does not by itself establish socio-economic inequality. A more comprehensive equity analysis would require integration of smart meter locations with poverty indicators, household income, informal-settlement boundaries, population density, service reliability and infrastructure investment. Spatial regression or inequality indices could then be used to determine whether meter deployment reduces or reproduces existing socio-economic disparities.

The household-level econometric findings provide additional evidence of an association between meter type and reported service outcomes. Households using prepaid meters had lower odds of reporting NRW-related experience than those using conventional meters ((\mathrm{OR}=0.71), (p=0.042)), after controlling for connection status, service-coverage category, education and household size. This suggests that prepaid-meter users were approximately 29% less likely to report water-loss experience than conventional-meter users. Connected households and households located in high-coverage wards also had lower odds of reporting NRW experience, showing that meter technology operates within a broader service environment.

The odds ratio should not, however, be interpreted as proof that prepaid meters directly reduced physical water losses. Reported NRW experience was based on household perceptions and may have captured visible leakage, billing irregularities, suspected meter errors or interruptions in service. Furthermore, households receiving prepaid meters may differ systematically from conventional-meter users in location, connection quality, service coverage and utility attention. The association may therefore reflect both metering effects and pre-existing differences in service conditions. Longitudinal or quasi-experimental studies would be required to determine whether households experience measurable improvements after conversion from conventional to prepaid meters.

Prepaid meter use was also positively associated with perceived billing accuracy ((\beta=+0.47), (p<0.001)). This finding suggests that prepaid-meter users were more likely to perceive their billing arrangements as accurate than households using conventional meters. Prepaid systems can improve transparency because payment is more closely linked to recorded consumption and customers can monitor their remaining credit. Nevertheless, billing accuracy depends on more than the physical meter. It also requires accurate customer databases, correct tariff programming, reliable vending systems, proper meter calibration, accessible complaint mechanisms and timely technical support. Meter installation without these supporting systems may not generate sustained improvements in customer confidence.

Policy awareness was moderate, with 59.1% of respondents reporting awareness of water-related policies and regulations. Awareness differed significantly by connection status and service-coverage category, indicating that households with stronger formal relationships with the utility were more likely to know about water-sector policies. Connected households may receive more information through billing notices, customer-service interactions, public meetings and utility communication channels. In contrast, unconnected and low-coverage households may have less contact with formal service institutions, limiting their exposure to policy information.

Perceptions of policy effectiveness and contribution to sustainability were also more positive in high-coverage areas than in low-coverage areas. This suggests that public assessment of water policy is shaped by actual service experience. Households receiving more reliable services are more likely to view policies as effective, while those experiencing limited access or weak service delivery may perceive a gap between policy commitments and practical outcomes. In relation to NAWAPO 2022 and the Water Supply and Sanitation Act No. 5 of 2019, the findings indicate that the principal challenge is not the absence of policy direction but incomplete implementation at local and service-area levels.

The policy implementation gaps were particularly evident in NRW control, equitable service expansion, tariff and billing reliability and utility-performance monitoring. Key informant evidence indicated that national policy direction was generally clear, but rapid urban growth, limited implementation capacity and coordination delays reduced its effectiveness. This finding is especially relevant in Dodoma, where population growth and physical expansion have increased pressure on groundwater sources, distribution infrastructure and institutional capacity. Policy implementation should therefore be assessed using measurable ward-level outcomes, including connection expansion, service continuity, NRW reduction, complaint resolution and equitable deployment of metering infrastructure.

Institutional partnerships were associated with urban water-service delivery through infrastructure development, regulatory oversight, technical assistance, public engagement and resource mobilisation. Participation in water-related meetings was positively associated with service satisfaction (($r=0.312$), ($p<0.001$)), although the relationship was modest. This finding suggests that households involved in consultation and engagement processes may have greater access to information, stronger communication with service providers and more realistic expectations regarding service constraints.

The association should not be interpreted as evidence that participation directly caused higher satisfaction. Households in better-served areas may have more opportunities to attend meetings, interact with utility representatives and participate in formal water-governance arrangements. Conversely, communities with limited services may have fewer organised engagement mechanisms. Effective participation therefore requires deliberate inclusion of low-coverage, peri-urban and unconnected households rather than relying solely on conventional public meetings.

Key informants reported that partnerships supported service improvement but were constrained by weak coordination and a mismatch between infrastructure demand and the speed of capacity expansion. This suggests that the contribution of partnerships depends on clearly defined institutional roles, reliable communication, shared data systems and alignment between investment priorities and urban growth. Partnerships should therefore be evaluated not only by the number of participating institutions or projects implemented but also by their contribution to measurable service outcomes.

Taken together, the findings support a socio-technical interpretation of urban water-service sustainability. Smart metering was associated with improved indicators in some years, wards and household groups, but its contribution depended on policy implementation, infrastructure condition, data quality, maintenance capacity, customer support and institutional coordination. The 2025 anomaly particularly demonstrates that technology alone cannot guarantee sustained reductions in NRW or improvements in revenue collection. Where meter records are incomplete, faulty devices are not replaced promptly, or network losses remain uncontrolled, the anticipated benefits of smart metering may weaken.

The integration of utility records, household survey data, GIS analysis and key informant evidence strengthens the overall interpretation by showing broadly consistent relationships across multiple analytical levels. Nevertheless, the evidence remains associative. Future studies should use longer time-series data, distinguish real from apparent NRW losses, verify smart meter functionality rather than relying only on installation records, and track households before and after meter replacement. Comparative analysis involving several Tanzanian urban utilities would also help determine whether the observed relationships are specific to Dodoma or represent broader patterns in urban water-service management.

5.0 Limitations of the Study

This study has several limitations. First, the utility-level time-series covered only five years, which limits the strength of trend analysis and makes the correlations sensitive to yearly anomalies, particularly the 2025 decline in smart meter coverage and increase in NRW. Second, the study used observational and cross-sectional data; therefore, the findings should be interpreted as associations rather than causal effects.

Third, some household-level indicators, including reported NRW experience, billing accuracy, and satisfaction, were based on self-reported responses and may be influenced by respondent perception. Fourth, the spatial equity analysis compared smart meter density with service-related indicators but did not include ward-level poverty or income data. As a result, the study could not conduct a full socio-economic spatial regression or inequality analysis.

Despite these limitations, the integration of utility records, GIS analysis, household survey data, and key informant evidence provides a useful multi-level understanding of smart water metering and urban water-service sustainability in Dodoma City.

6.0 Conclusion

Smart water metering was associated with selected improvements in urban water-service performance in Dodoma City, particularly in relation to NRW, revenue collection, billing accuracy, and customer satisfaction. However, these relationships should be interpreted as correlational rather than causal because the study used observational data and a short utility-level time series.

The uneven spatial distribution of smart meters indicates that potential metering-related benefits may not be equally distributed across wards. Future deployment should therefore prioritise under-served and peri-urban areas while strengthening maintenance, data management, customer support, and institutional accountability.

The findings also show that policy frameworks and partnerships remain essential for sustainable urban water-service delivery. Smart metering should be implemented as part of an integrated approach that combines technology, equitable planning, regulatory enforcement, and coordinated institutional support.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Data availability

The datasets used in this study are available from the corresponding author upon reasonable request. Anonymised household survey data and GIS-derived ward-level indicators may be shared for academic verification, subject to institutional approval and protection of respondent confidentiality.

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