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Governance, Financing, and Digitalisation to Reduce Non-Revenue Water (NRW): Adoption and Strategies (Case Study: Jakarta)

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Abstract. Urban water utilities often face a service paradox: production capacity may exist, yet reliable and billable delivery remains constrained by distribution losses. Non-revenue water (NRW) is a central manifestation of this challenge because it simultaneously erodes utility revenue, strains operations, and can worsen reliability and equity. This study examines NRW reduction in Jakarta (PAM JAYA) using a three-pillar lens: governance, financing, and digitalisation, to understand adoption conditions beyond device deployment. Evidence was assembled from benchmarking and utility artefacts and one semi-structured interview session involving multiple stakeholders (directors, division heads, and operational teams), with confirmation of key points during the session. The analysis applies CFIR-informed qualitative coding and synthesizes a within-case adoption profile across the three pillars. Results show that NRW remained persistently high during 2015–2023 (mid-40% range in recent years) despite variation in other internal service and operational indicators. The case exhibits a formal mandate and an expanding toolkit of digital/field practices (e.g., DMA segmentation, SCADA-supported pressure management, targeted metering), alongside financing preparations for large-scale programs. However, reported constraints, particularly the need to strengthen routines, capability independence, and consistent use of monitoring outputs to trigger and verify field actions, suggest a durability gap that can limit sustained NRW improvement. The paper concludes with practical implications for aligning mandates, financing pathways, and governed operational use of digital tools to make NRW reduction gains stick in metropolitan utilities.

Keywords: Non-Revenue Water (NRW), Governance, Financing, Digitalisation (DMA/AMI/SCADA), CFIR, Jakarta

1. Introduction

Urban water utilities in fast-growing metropolitan areas often face a persistent service paradox: production capacity can exist, yet reliable and billable delivery at the customer tap remains constrained by distribution losses and operational fragility. A core manifestation is non-revenue water (NRW), water that enters the system but does not generate revenue due to real losses (leakage and bursts), apparent losses (meter inaccuracies and unauthorized consumption), and authorized but unbilled consumption. High NRW therefore represents both a technical inefficiency and a governance–finance challenge because it reduces cash flow while increasing operational burdens. When NRW is high, utilities can struggle to cover operation and maintenance (O&M) needs and to mobilize funds for capital renewal, reinforcing a cycle of deterioration and persistent losses [1], [2], [3].

High NRW also undermines service reliability and equity. Real losses and bursts can drive pressure fluctuations and supply interruptions, increasing the need for pressure management and proactive maintenance to stabilize service [3]. In many settings, the financial stress associated with NRW constrains service expansion. It can intensify inequities, as utilities face difficult trade-offs between network rehabilitation and extending reliable service to low-income areas and informal settlements. These equity dynamics are increasingly emphasized in recent studies linking NRW to affordability, differentiated service levels, and utility decision-making under resource constraints [4], [5].

Despite wide recognition that NRW is reducible, many programs underperform when loss reduction is treated primarily as an engineering problem solved by device deployment. Recent implementation-oriented literature highlights recurring barriers that can prevent district metered areas (DMAs), supervisory control and data acquisition (SCADA), and advanced metering technologies from translating into sustained NRW reduction. These barriers include weak accountability routines when leakage is estimated rather than measured, limitations in data quality and system integration, and gaps in data governance needed for credible baselines and verification [6], [7]. Utilities also face O&M capacity constraints and coordination challenges, including interoperability and cybersecurity issues in digital water systems that can limit the effective operational use of collected data [7], [8].

Durability is further challenged by relapse mechanisms, where early improvements erode over time if institutionalisation is incomplete. Evidence from recent NRW programs emphasizes the importance of sustained investment, long-term planning, and organisational arrangements that maintain accountability and focus [9], [10]. Common institutionalisation factors include standard routines and procedures (e.g., pressure management and systematic leakage control), timely repairs, and verification protocols that ensure that reported savings remain credible and maintained [3], [9]. Taken together, these findings support a framing of NRW reduction as an implementation problem in which governance discipline and financing realism condition the effectiveness of digital tools.

This study adopts a three-step pathway lens, governance, financing, and digitalisation, to structure the assessment of NRW reduction adoption and related implementation conditions. The "Three-Step Pathway" emphasizes that digital interventions (e.g., DMA/SCADA and metering) are most effective when governance arrangements (mandates, accountability, routines) and financing mechanisms (investment frameworks and cost recovery pathways) support sustained operations and renewal [11]. Jakarta provides a high-learning metropolitan case because NRW reduction and service expansion are pursued under a formal mandate and a system transition context, alongside the exploration of financing instruments and the deployment of operational digital tools [12].

Accordingly, this paper addresses two research questions: RQ1: What is the observed adoption profile of NRW reduction across governance, financing, and digitalisation in Jakarta (PAM JAYA)?, and RQ2: What implementation barriers and enabling conditions explain uneven adoption across the three pillars?. This paper contributes an implementation-focused adoption profile of NRW reduction in Jakarta structured by the governance–financing–digitalisation pathway, highlighting key conditions associated with uneven uptake across the three pillars. The paper presents the case results on the three-pillar adoption profile, then discusses the main implementation barriers and enabling conditions, and concludes with practical implications for sustaining NRW reduction.

2. Methods

This study applies a single-case design focusing on Jakarta (PAM JAYA) to examine NRW reduction adoption across the governance–financing–digitalisation pathway. Evidence was assembled from (i) sector/benchmarking references, (ii) PAM JAYA artefacts (e.g., selected SOP and dashboard materials where available), and (iii) one semi-structured interview session conducted with multiple utility stakeholders (including directors, division heads, and field/operational teams), enabling real-time confirmation of key points during the discussion.

Analysis proceeded in two steps. First, interview and artefact evidence were coded using the Consolidated Framework for Implementation Research (CFIR 2.0) to identify barriers and enablers across intervention characteristics, outer/inner setting, individual characteristics, and implementation process [13]. Second, a within-case Adoption Profile was constructed for each pillar: governance (mandates, accountability routines), financing (funding/cost-recovery readiness and enabling instruments), and digitalisation (DMA/SCADA/metering practices and data stewardship), to summarise observed adoption and maturity gaps [11].

Given the single-case scope and the reliance on a structured interview session, findings are analytically transferable to similar metropolitan utilities but not statistically generalizable; triangulation across sources was used to reduce interpretation bias [14].

Table 1. *Method overview.*

Element	Description
Case	Single case: Jakarta (PAM JAYA)
Evidence	Benchmarks; selected utility artefacts; one multi-participant interview session
Framework	CFIR coding + three-step pathway (Government – Finanncing – Digitalisation)
Outputs	Adoption Profile per pillar + CFIR-mapped barriers/enablers

3. Results

3.1 Performance trajectory (2015–2023)

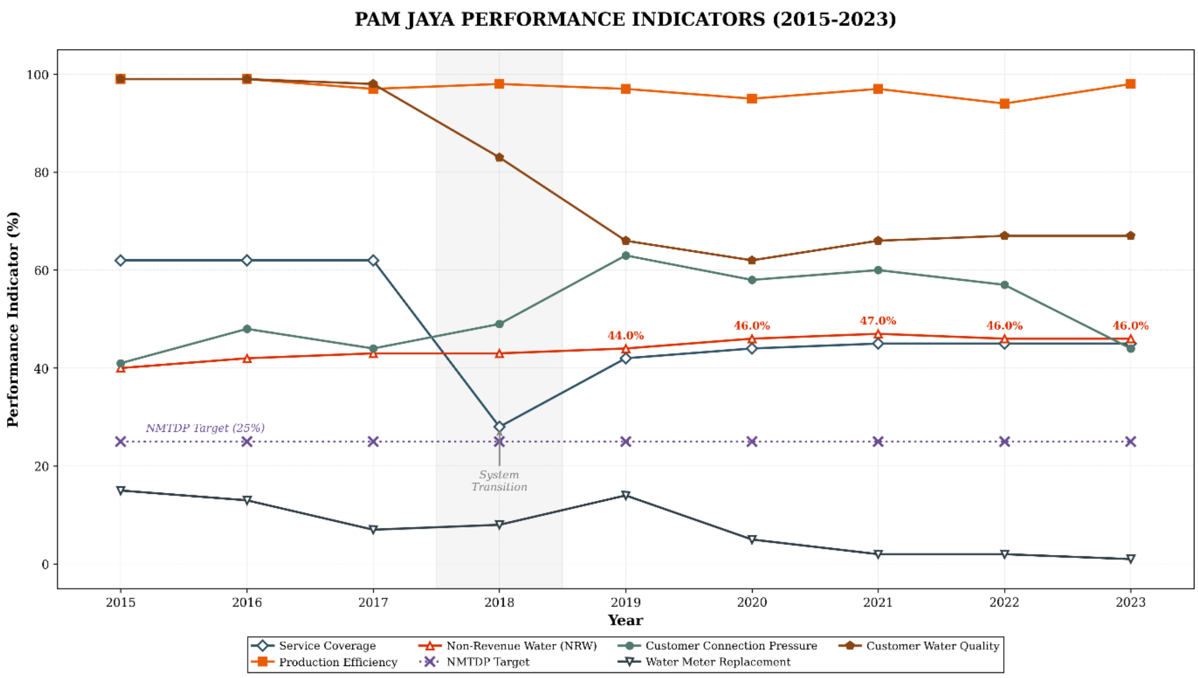

Figure 1. *PAM Jaya internal performance indicators (2015-2023)*

Figure 1 shows NRW remaining high during 2015–2023 and consistently above the 25% national target reference line shown in the figure. The annotated NRW values in the later period are 44.0% (2019), 46.0% (2020), 47.0% (2021), and 46.0% (2022–2023). Over the same period, other internal indicators (service coverage, production efficiency, customer connection pressure, water quality, and water meter replacement) also vary, indicating that service and operational conditions evolved while NRW remained materially high. A recent reference point in the case materials reports NRW at approximately 45.88% by December 2024.

3.2 Governance: mandate, accountability, and routines

The case is anchored in a formal mandate and a governance transition. Governor Regulation DKI Jakarta No. 7/2022 assigns PAM JAYA to accelerate service delivery while controlling NRW, including a stated trajectory toward full service coverage by 2030 and an associated NRW reduction pathway with interim targets. The case materials also describe a post-concession transition, with the prior concession arrangement ending on Feb. 1, 2023, after which PAM JAYA assumed full system management.

The institutional setting is linked to the selection of delivery and partnership instruments. PAM JAYA's status as a regional utility (BUMD/Perumda) is described as shaping partnership flexibility and motivating exploration of mechanisms such as bundling financing, PPP/KPBU, and performance-based approaches for NRW reduction. Questionnaire/interview responses also highlight implementation needs related to operational routines and capability building, including reliance on vendor or third-party training/certification for certain tools and the need to strengthen procedures so that monitoring outputs translate into consistent operational action.

3.3 Financing: funding pathway, constraints, and instruments

The case materials position NRW reduction alongside large-scale service expansion and enabling financing instruments. In 2023, approximately IDR 35 billion (Regional Capital Participation) was allocated to support preparatory work, including an NRW roadmap and feasibility activities. A bundling financing vehicle (PT Air Bersih Jakarta/ABJ) was established for collaboration with a private partner, and an agreement was signed on Oct. 14 2022. The materials also reference credit/financing support (including syndicated credit) and pipelining needs on the order of approximately 7,000 km, indicating a capital-intensive expansion context alongside NRW control.

Table 2. *Financing-related evidence in the PAM JAYA case materials, including preparation funding and reported scale requirements.*

Evidence item (as reported)	Reported statement/value	Descriptive implication
Preparation funding	~IDR 35 billion (Regional Capital Participation) for preliminary studies (NRW roadmap/feasibility)	Enabling work to initiate/structure the program
Bundling vehicle	ABJ established; agreement signed Oct. 14, 2022	Partnering/financing arrangement for delivery
Network expansion scale	~7,000 km pipelining referenced	High CAPEX context alongside NRW control

3.4 Digitalisation: tools deployed, utilisation, and operational practices

The case materials describe a mix of field technologies and monitoring tools used for NRW control. The leakage detection toolbox includes helium tracer, ground penetrating radar (GPR), leak correlators, smart ball, endoscopy, and pipeline inspection cameras (CCTV).

Questionnaire/interview responses describe digitalisation practices combining monitoring, segmentation, and targeted repair. Reported practices include pressure management supported by supervisory control and data acquisition (SCADA) analysis and district metered area (DMA) segmentation, advanced metering reading (AMR) for corporate customers and DMA inlet points, internal asset condition assessment calculations, and a trial use of a sealant technology for leakage repair. Reported effects include improved leak localization through segmentation, improved characterization of leakage frequency by pipe attributes (type/age/length), and faster repair in the trial context.

Several utilisation and capability constraints are also reported, including reliance on vendor/third-party training for certain competencies and the need to strengthen routines and procedures so that devices and monitoring outputs are used consistently to trigger operational action.

Table 3. *NRW-related operational and digitalisation practices reported in questionnaire/interview responses, including stated effects and constraints.*

Practice area	Reported practice	Stated effect	Stated constraint
Monitoring & control	SCADA analysis + DMA segmentation for pressure management	Supports NRW reduction in DMAs through pressure management	Routines/SOP strengthening and utilisation issues noted
Metering & measurement	AMR for corporate customers and DMA inlet points	Improves calculation/measurement through DMA refinement	Training/certification still vendor-dependent
Asset analytics	Asset condition assessment calculations	Supports leakage characterization by asset attributes	Data integration/standardisation needs implied
Leakage repair	Sealant trial	Faster repair in trial context	Scaling/institutionalisation conditions not yet established

4. Discussion

4.1 What the Performance Trajectory Implies: A “Durability” Problem, Not a Visibility Problem

The Results show that NRW remained persistently high across 2015–2023 (and still around the mid-40% range in a recent internal reference point), even as other internal service and operational indicators varied over time. This pattern suggests that the case is less constrained by problem visibility, because the organisation already tracks performance and deploys multiple monitoring tools, and is more constrained by durability conditions: the ability to repeatedly convert information into verified action (prioritise, repair, confirm, and sustain). In practice, utilities can experience noticeable operational changes without seeing a material NRW decline when leakage control is not "locked in" through a stable cycle of detection, response, and verification that persists beyond pilots or episodic campaigns [3], [15].

The same interpretation helps reconcile the apparent paradox in the trajectory: service conditions can evolve (coverage, efficiency, pressure, water quality, meter replacement), yet NRW remains sticky. NRW is not only a technical outcome but also a behavioural and organisational outcome, shaped by whether field execution, metering/measurement, and reporting disciplines operate as a coherent production system. Where that coherence is incomplete, early improvements can be difficult to accumulate into a multi-year downward trend because interventions are not consistently verified, learning loops are weak, or repairs are not systematically prioritised and closed out [16].

4.2 Why Adoption Can Be Uneven: Mandate and Tools Move Faster than Routines and Capability

The Results indicate a strong formal mandate (Governor Regulation DKI Jakarta No. 7/2022) and a governance transition after the concession ended in February 2023, but also report ongoing needs to strengthen routines so that monitoring outputs consistently trigger operational action, alongside vendor/third-party training dependencies. This combination is a common implementation pattern: mandates and technology purchases can move quickly, while the slower work is building routines, role clarity, and capability independence that make the system perform every week, especially in large utilities where cross-unit coordination is required to translate analytics into field work and then into verified performance.

The implications for Jakarta are practical. First, vendor-dependent competencies can create "single points of failure" for sustained operations: when key skills or certifications sit outside the utility, the use of tools may be intermittent, inconsistent across areas, or concentrated in a few teams. Second, routine gaps mean that monitoring can become informational rather than operational, producing signals that do not reliably trigger standard responses. Both issues matter because NRW reduction depends on the repetitive execution of many small actions (find, isolate, repair, retest), not a one-time intervention. Prior evidence on NRW programs supports the same logic: durable reduction is typically associated with disciplined, holistic operating models rather than technology alone [3], [15].

4.3 Interpreting the Three Pillars Together: What Should Be Reinforced to Make Gains Stick

The Results show simultaneous movement across governance, financing instruments, and digital operations, but also point to utilisation and institutionalisation constraints. Interpreting these findings together yields a focused "durability agenda" for each pillar:

- **Governance**. The presence of a formal mandate and a post-concession consolidation creates a credible foundation for clearer accountability. The key interpretation, however, is that the mandate's value depends on whether it is translated into an operating system: standard routines (who does what, when), escalation paths, and performance cadences that keep DMA performance, pressure management responses, and repair completion visible and non-negotiable. Without these routines, a mandate can coexist with persistent NRW because execution is uneven and cross-unit coordination remains fragile.
- **Financing**. The Results describe enabling preparation funding (regional capital participation) and a bundling vehicle (ABJ), while also describing a highly capital-intensive expansion context. The interpretation is not merely that "more finance is needed," but that financing must be structured to support repeatable NRW operations and network renewal alongside expansion. Broader tariff and cost recovery literature emphasizes that utilities' ability to sustain performance depends on stable revenue adequacy and credible investment pathways, because leak control, metering upkeep, and pipe renewal require continuous funding rather than episodic budgets [17], [18].
- **Digitalisation**. The Results describe extensive field toolkits and the operational use of SCADA, DMA segmentation, and AMR for priority measurement points, with reported benefits in leak localization and faster repairs in trials. The critical interpretation is that digitalisation already exists in practice. However, its contribution to sustained NRW reduction depends on whether information is governed: consistent definitions (e.g., DMA performance metrics), reliable measurement points, traceable interventions, and verification routines. Evidence from DMA + smart metering implementations shows that the value of digital tools rises when measurement and leakage estimation are disciplined and comparable over time [6], while unstable access to accurate measurement and field realities can drive apparent

NRW fluctuations that blur whether performance is truly improving [16]. In this sense, Jakarta's constraint is less "which devices to add" and more "how to ensure devices consistently produce actionable, auditable signals inside a routine-driven operational model" [19].

4.4 Transferability: What Jakarta Contributes to Other Metropolitan Utilities

The Jakarta case is informative for other metropolitan utilities pursuing NRW reduction while simultaneously expanding service coverage. The first transferable insight is that high NRW persistence despite evolving service indicators and technology uptake signals a need to prioritize durability conditions: institutionalised routines, capability independence, and verification discipline that converts monitoring into sustained action [3], [15]. The second transferable insight is that governance transitions can create a window for reform, but they also increase execution risk if routines and competencies are not embedded quickly; vendor-dependent skills and inconsistent utilisation weaken the utility's ability to scale beyond pilots.

For policy and implementation design, the case suggests that three elements should be aligned: (i) governance that specifies not only targets but also operating cadences and accountability; (ii) financing pathways that sustain renewal and NRW operations over multi-year horizons (revenue adequacy and investability); and (iii) digitalisation that is treated as governed information (definitions, stewardship, verification) rather than a set of devices [17], [19].

5. Conclusion

This paper finds an uneven adoption profile across the governance–financing–digitalisation pillars in Jakarta (PAM JAYA): formal mandates and active operational digital tool use are present, while NRW remains persistently high. The results indicate a durability constraint, monitoring, and devices exist. However, routines, capability independence, and verification discipline are not yet embedded strongly enough to convert information into repeatable, auditable action at scale. Practically, utilities should prioritize institutionalising accountability cadences (standard routines, escalation paths, performance reviews) and strengthening data governance so DMA/SCADA/metering outputs reliably trigger field interventions and confirm savings. Financing instruments should be aligned to sustain multi-year NRW operations and network renewal, rather than treating NRW control as a one-off technical campaign. As a single-case study, the findings are analytically transferable but not statistically generalizable; future work will test the same adoption profile through a cross-sectional, multi-case design across metropolitan utilities to assess consistency of barriers/enablers and to refine actionable implementation guidance.

Data availability statement

The analyzed data are available from the corresponding author upon reasonable request.

Underlying and related material

No underlying or related material has been deposited in a public repository.

Author contributions

R. Wirahadikusumah: Conceptualization; Supervision; Methodology; Validation; Writing – review & editing. M. A. Viqolbi: Conceptualization; Investigation; Data curation; Formal analysis; Visualization; Writing – original draft; Writing – review & editing. H. Kardhana: Investigation; Data curation; Validation; Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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