Public Private Partnerships for Sustainable Urban WASH Infrastructure Development

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Abstract: *This study presents an operational conceptual model to support urban water, sanitation, and hygiene (WASH) public-private partnerships (PPPs) when contracting decisions must be made under fiscal stress and fragmented governance. Existing PPP lenses often remain descriptive, which limits consistent selection of contract forms and weakens accountability for service reliability, affordability, and equity outcomes. The proposed framework maps urban context to PPP type-context fit through explicit constructs and boundary conditions, and it is paired with a coding rubric and a programmatic cohort specification designed for grouped holdouts across external context groups and baseline comparisons. Evaluability is strengthened by defining affordability as a cost vs cap ratio with pass criteria of <= 1.0, and by requiring uncertainty reporting via BCa bootstrap with 95% confidence intervals. Construct coding is supported by independent review, with 2 annotators and 15% dual coding plus adjudication to limit silent drift. The resulting package converts theory synthesis into testable propositions and auditable decision rules, while retaining clear non-applicability zones where site-specific engineering or procurement detail is required. This decision-oriented framing has direct implications for contracting authorities, regulators, and urban utilities seeking PPP designs that protect affordability and accountability alongside measurable service KPIs.*

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Introduction

Urban water, sanitation, and hygiene (WASH) public-private partnerships (PPPs) are often selected under fiscal stress, yet their performance hinges on governance capacity, stakeholder alignment, and sustained service incentives. Prior syntheses argue that sustainable city PPP success depends on interconnected themes spanning governance, public-private-people partnerships, sustainability, and innovation (Leshinka et al., 2023), and that megacity WASH outcomes require public oversight that can temper profit-oriented private logics (Ferreira et al., 2022). Decision rules remain insufficiently operational for urban service settings.
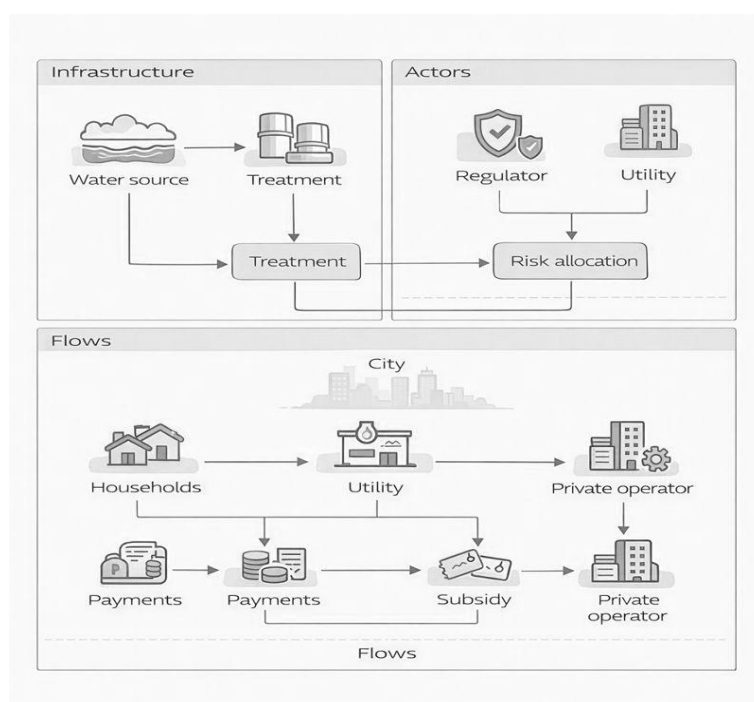
Figure 1. *Urban WASH PPP field context*

The present study develops an operational conceptual model that maps urban context to PPP type-context fit and formulates testable propositions, extending

sustainability-oriented PPP framing toward implementable decision logic (Leshinka et al., 2023). Research design transparency is supported by outlining the sequence from theory synthesis to a coding rubric, followed by validation on an Urban WASH PPP Contract Performance Cohort using grouped holdouts across external context groups. Fig. (1) anchors the discussion in a service setting salient to SDG 6 governance challenges (Ferreira et al., 2022).

Background and Related Foundations

Urban WASH PPP scholarship typically separates enabling conditions, financing instruments, and public-sector innovation barriers, which complicates consistent project-type selection. Fig. (2) situates widely used baseline lenses and clarifies the incremental contribution of the proposed context-to-decision model. Risk profiles and financing determinants are documented across development portfolios and national studies, highlighting fiduciary and capacity constraints and the limits of commercialization without de-risking (Heckel, 2023; Machete & Marques, 2023; Mundonde & Makoni, 2023; Mutandwa & Vyas-Doorgapersad, 2023). Smart-city PPP governance and innovation ecosystems further stress institutional readiness and stakeholder alignment (Akgün et al., 2024; Biygautane & Clegg, 2024; Cambra-Fierro et al., 2023; CHEWA et al., 2022; Hedegaard et al., 2024; Hossain et al., 2024; Mathew & Bangwal, 2024; Nylen et al., 2022; Santopietro & Scorza, 2024; Trimmer et al., 2023).
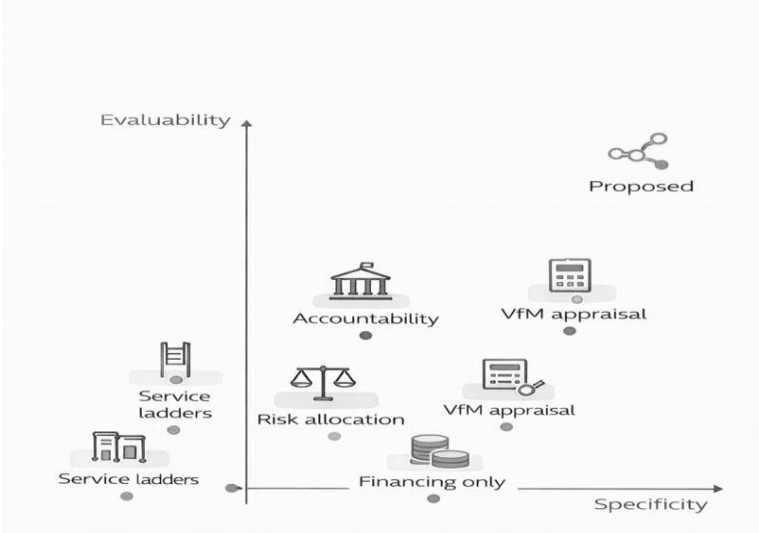
Figure 2. *Baseline frameworks and value-added*

Affordability and equity baselines emphasize indicator choice and distributional effects under tariffed services, including multidimensional affordability assessment and discourse evidence on privatization risk for vulnerable groups (Fagundes et al., 2023, 2025; Neves-Silva et al., 2023; Phạm, 2025; Wu et al., 2022). Participation mechanisms range from locally led coalitions and co-design to state-society relations that sustain collective management, with lessons from living labs and adaptive programming in fragile settings (Frick-Trzebitzky et al., 2022; Grant & Willetts, 2024; Kirk et al., 2023; Pool et al., 2023; Thapa et al., 2022). Evidence corpus integrity remains bounded by heterogeneous designs and contexts; explicit inclusion and exclusion rules are not reported here, and comparable evaluative scorecards are still emerging (Behsoodi et al., 2023; Genter et al., 2023; Singh et al., 2022; Wong et al., 2025).

Conceptual Framework

The proposed framework treats urban WASH public-private partnership (PPP) choices as outcomes of structured interaction among public agencies, private operators, financiers, and communities. Drawing on network-based accounts of city climate-responsiveness, city networks are viewed as operative components that shape local investment priorities and coordination capacity rather than as mere normative backdrops (Santopietro & Scorza, 2024). This lens motivates a focus on relational channels (information exchange, trust, and alignment around targets) that condition feasible contract forms and risk allocation.

Actor-interaction channels are translated into decision constraints by linking observed coordination capacity to expected service reliability, affordability, equity, and accountability outcomes. Community awareness and commitment, emphasized as practical success conditions in voluntary planning networks (Santopietro & Scorza, 2024), are treated as prerequisites for sustaining tariff policies and grievance redress that underpin accountability score and affordability impact index. The framework is intended for urban contexts where multiple actors bargain under climate and resource shocks; it is not a substitute for site-specific engineering design.

Key Constructs and Definitions for Urban WASH PPP Decisions

Urban WASH PPP decisions are encoded as a small set of enabling-environment constructs that support comparable assessment across cities. Fig. (3) standardizes construct definitions and units to reduce interpretive drift when applying the rubric in heterogeneous institutional settings. The construct set follows prior comparative work on inclusive, citywide piped services, emphasizing provider functionality and explicit pro-poor policy commitments (Trimmer et al., 2023). Conceptual precision is enforced by keeping the unit of analysis at the project level.

Table (1) defines four measurable constructs and links each to an operational indicator and coding rule. Expected KPI Attainment is captured as target met proportion under a project-level, grouped holdout design, while Grouped Holdout Generalization records the leave-group-out delta with an explicit no-leakage constraint. Affordability uses a cost vs cap ratio, with passing defined as <= 1.0, consistent with reviewed indicator and threshold debates (Fagundes et al., 2023, 2025). Accountability is rubric coded by two annotators.
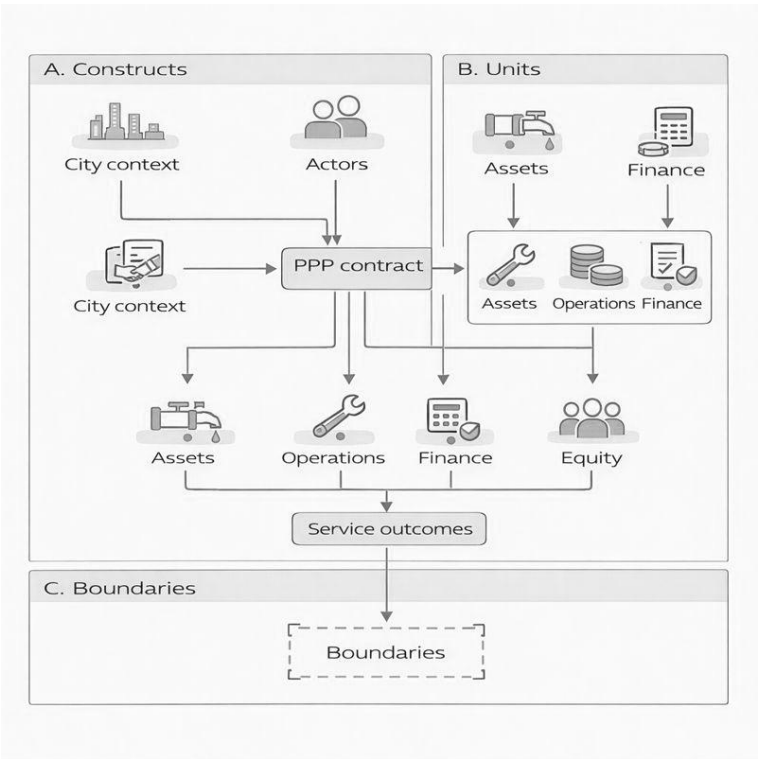

Figure 3. *Constructs, units, and definitions*

Table 1. Key constructs and definitions

Construct	Operational Indicator	Coding Rule
Expected KPI Attainment	Target met proportion	Project-level; grouped holdout
Affordability Impact Index	Cost vs cap ratio	Pass if <= 1.0
Accountability Score	Governance compliance score	Rubric coded; 2 annotators
Grouped Holdout Generalization	Leave-group-out delta	No cross-split leakage

Boundary Conditions for Affordability Caps and Operator Capacity

Affordability caps constrain public-private partnership (PPP) designs when tariffs are expected to remain within a politically and socially acceptable ceiling, and they become fragile when full cost recovery is treated as a non-negotiable financing condition (Heckel, 2023). As defined in Equation (1), the affordability impact index expresses per-person PPP cost relative to the cap, so values above unity indicate a binding burden. Supplier-side subsidy and revenue risks can still undermine viability, especially where markets are thin (Phạm, 2025).

Operator capacity is bounded by feasible response times and fails where demand surges create overrun risk. As defined in Equation (2), capacity slack measures normalized headroom between the response-time cap and the expected response time. Regulator-utility dynamics matter for sustaining that headroom because clarity, continuity, and bounded flexibility shape operational adaptation (Nylen et al., 2022). Table (2) summarizes these boundary conditions, including limits arising from governance readiness and the use of aggregate rather than individual data.

$$AffordabilityImpactIndex = \frac{C_{ppp}}{C_{cap}} \qquad (1)$$

$$CapacitySlack = \frac{t_{cap} - t_{resp}}{t_{cap}} \qquad (2)$$

Table 2. Boundary conditions and limits

| Boundary	Applies When	Fails When	Design Cue
No individual data	Aggregate statistics only	Individual linkage needed	Policy-only outputs
Affordability cap	Tariffs within cap	Full cost recovery	Affordability constraints (Heckel, 2023)
Operator capacity	Response time feasible	Capacity overrun risk	Capacity limits (Mutandwa & Vyas-Doorgapersad, 2023)
Governance readiness	Legal oversight exists	Weak institutions	Governance prerequisites (Leshinka et al., 2023)},{

Propositions and Implications

The present study advances propositions that tie Public-Private Partnership (PPP) governance and explicit pro-poor policy to urban service performance. Comparative evidence on citywide piped water provision indicates that provider functionality and pro-poor rules recur across progress pathways (Trimmer et al., 2023). This pattern implies that governance arrangements influence reliability and equity through day-to-day provider operations. Building on PPP process themes, governance and public-private-people partnership design are treated as jointly enabling accountability and affordability (Leshinka et al., 2023). These linkages yield observable expectations for expected KPI attainment rate, affordability impact index, and accountability score.

Risk-mitigation propositions are aligned with prevalent water supply and sanitation (WSS) risk profiles (Machete & Marques, 2023). Fiduciary, institutional capacity, environmental and social, and political-governance risks are treated as primary threats to sustained service delivery. The implication is testable: PPP designs that allocate risk without matching mitigation capacity should exhibit weaker accountability score and affordability impact index. Innovation and sustainability elements in PPP processes matter insofar as they strengthen mitigations through enforceable governance routines (Leshinka et al., 2023).

Competing explanations, such as financing availability alone, remain plausible and require empirical discrimination.

Causal Mechanisms Linking Risk Allocation to Service KPIs

   Risk allocation in urban WASH public-private partnerships is treated as a causal driver of key performance indicators (KPIs) because it reassigns incentives, capital costs, and monitoring duties. Using empirically observed water supply and sanitation (WSS) risk types such as fiduciary, institutional capacity, environmental and social, and political and governance risks (Machete & Marques, 2023), the mechanism links misallocated risks to underinvestment in mitigation and weaker enforcement. Fig. (4) formalizes these causal logic and mechanisms as directed paths from risks to KPI attainment.
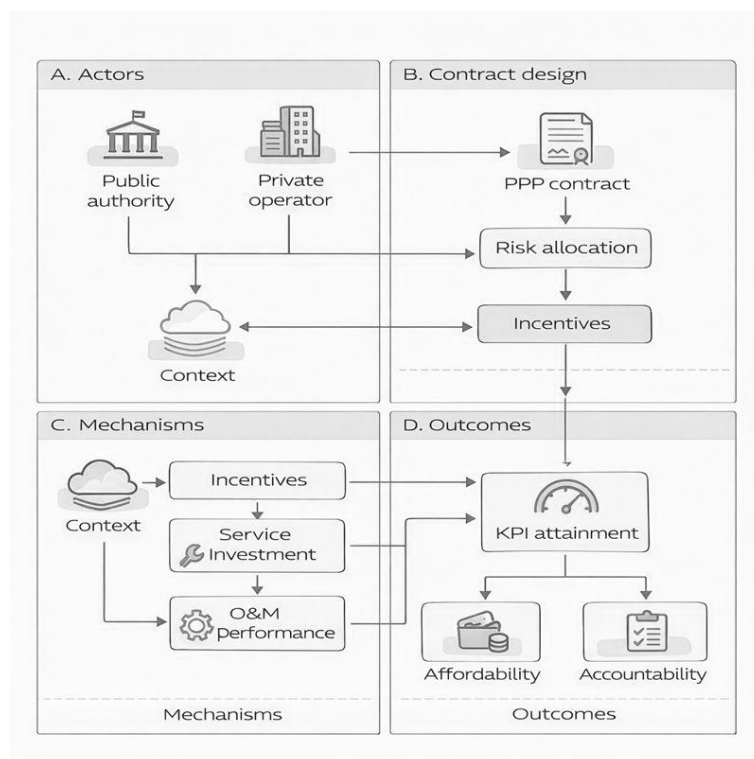
Figure 4. *Mechanisms from risks to KPIs*

   Financial viability operates as the transmission channel between risk allocation and service reliability when affordability limits tariff recovery. Evidence from private-sector WASH suppliers indicates that revenue instability, operational cost shocks, and household affordability constraints can force deferred maintenance

and intermittent service, even when access objectives are met (Phạm, 2025). Business-model scorecards justify KPI selection by tying institutional and financial criteria to observable delivery outcomes, including accountability and scalability (Singh et al., 2022). Boundary conditions remain: effects weaken where transfers fully cover operating costs.

Alternative Explanations for KPI Attainment Under Governance Fragmentation

Observed KPI attainment under fragmented governance can plausibly arise from state-society relations rather than from the proposed coordination mechanism alone. Variation in how participation is implemented, and in the social relations between local authorities and user groups, can lock in collective management pathways or trigger exit, with downstream effects on service reliability and accountability (Thapa et al., 2022). This alternative explanations lens implies that similar PPP designs may perform differently when frontline relations differ.

A second competing account is that informal public-private partnerships primarily build municipal and operator capacity, which then improves KPI attainment indirectly, even if governance fragmentation persists (Frick-Trzebitzky et al., 2022). A third mechanism is interest-group influence over procurement, staffing, or tariff decisions, which can degrade service delivery or reallocate benefits without changing formal arrangements (CHEWA et al., 2022). Discriminating among these alternative explanations requires evidence on timing, actor incentives, and decision pathways, which is not reported here.

Robustness Stress Tests Under Climate and Resource Constraints

Robustness under climate shocks and resource constraints is a design requirement for urban WASH PPP decision support. Table (5) defines stress scenarios, expected failure patterns, and the corresponding halt or guardrail. The Affordability Cap Bind and Demand And Cost Shock cases pressure affordability commitments and trigger the AC2 gate or a misuse checklist halt. Low Operator Capacity tightens response bounds and anticipates service reliability drop, reflecting SDG 6 megacity governance challenges (Ferreira et al., 2022) and evidence on urban resource efficiency limits (Hossain et al., 2024).

The robustness of reasoning is further exercised by weakening institutional assumptions rather than only varying costs. Regulatory Capacity Low introduces cross-context strata and anticipates an accountability score fall, with an external holdout check acting as the stop condition. Governance Features Removed serves

as a governance ablation and expects accountability degradation, halted by an overlap baseline. This framing matches city-network accounts in which climate responsiveness depends on actor interaction and capacity, not solely formal rules (Santopietro & Scorza, 2024).

Table 3. Stress tests and scenarios

Stress Scenario	Implementation Cue	Expected Failure Pattern	Halt Or Guardrail
Affordability Cap Bind	Clip cost fields	KPI gain collapses	AC2 gate enforced
Low Operator Capacity	Tighten response bounds	Service reliability drop	QC blockers halt
Demand And Cost Shock	Stress test ranges	Affordability breach risk	Misuse checklist halt
Regulatory Capacity Low	Cross-context strata	Accountability score fall	External holdout check
Governance Features Removed	Governance ablation	Accountability degradation	Overlap baseline halt

Evaluability: Decision Rules and Validation Plan Using Grouped Holdouts

Grouped holdouts were adopted to make the decision rubric evaluable under external context shifts, while keeping baseline comparisons explicit. Fig. (5) outlines the leave-group-out validation blueprint and the baseline comparators. Table (3) specifies grouped splits, baselines (LogReg, GBT, rules), primary metrics, and acceptance cues linked to logged artifacts. For baselines, improvement is judged by beating baseline CIs, not point estimates. Baseline selection aligns with established WASH sustainability scoring and scorecards, which provide domain-standard reference points (Behsoodi et al., 2023; Singh et al., 2022).

Evaluability rests on observable indicators. Equation (3) defines the grouped KPI attainment rate as the average outcome within group g, enabling leave-group-out scoring. Uncertainty is reported using BCa bootstrap with 95% CI and FDR control, and Equation (4) describes the percentile interval used for these bounds.

Research design transparency is enforced through split_hashes.json, seed_log.csv, config.yaml, and manifest_sha256.txt. Finance covariates follow PPP investment determinant evidence (Mundonde & Makoni, 2023), while feasibility signals draw on willingness-to-pay and participation measures (Wu et al., 2022).

$$\widehat{p_g} = \frac{1}{N_g} \sum_{i \in g} y_i \tag{3}$$

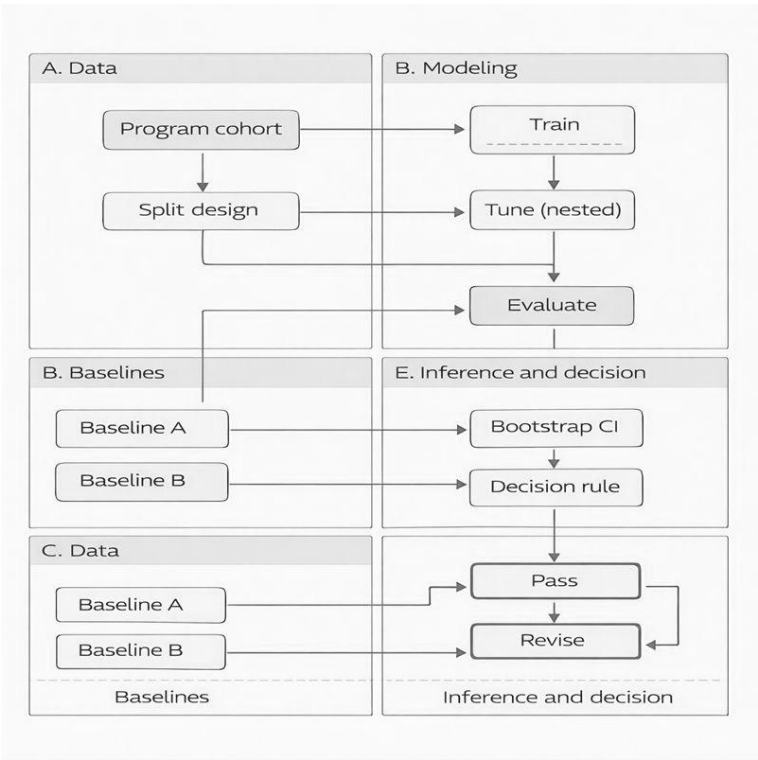$$CI_{1-\alpha}(\theta) = \left[\theta^*_{\alpha/2}, \theta^*_{1-\alpha/2}\right] \tag{4}$$

Figure 5. *Grouped holdouts and decision rules*

Table 4. Validation protocol summary

Protocol Element	Specification	Acceptance Cue
Splits	Grouped holdouts	Leave-group-out
Baselines	LogReg, GBT, rules	Beat baseline CIs
Primary Metrics	KPI rate, affordability, accountability	AC1-AC3 thresholds

Uncertainty	BCa bootstrap	95% CI, FDR

Programmatic Cohort Specification for Urban WASH PPP Contract Performance

Programmatic cohort specification targeted variables that proxy household coping and source choice under unreliable service, which are often omitted from contract records (Genter et al., 2023). Table (4) organizes the cohort specification into three columns and five cohort fields, linking each field to its source type (public aggregates, public reports, an entity registry, or dual annotators) and an explicit leakage control. Evidence corpus integrity was reinforced through holdout splitting before labels, train-only scaling, and constraints that prevent cross-split context group IDs.

Research design transparency is maintained by stating how outcomes, costs, governance features, and context group IDs were sourced and transformed, with preprocessing fit on training data only. Governance features were stress-tested via ablation checks and cohort inclusion criteria were aligned to enabling-environment dimensions relevant to citywide service delivery (Trimmer et al., 2023). Annotator rubric codes were produced by dual annotators and adjudicated on disputes, which limits silent drift in qualitative coding. These controls support evaluable, leakage-resistant grouped holdouts, although finer within-city heterogeneity is not reported here.

Table 5. Cohort spec and leakage controls

Cohort Field	*Source Type*	*Leakage Control*
Service KPI outcomes	Public aggregates	Holdout split before labels
Cost and tariffs	Public aggregates	Train-only scaling
Governance features	Public reports	Ablation checks
Context group IDs	Entity registry	No cross-split IDs
Annotator rubric codes	Dual annotators	Adjudication on disputes

Limitations and Future Work

Key limitations arise from political economy and discourse dynamics that shape PPP narratives and may not be fully represented in a programmatic cohort (Neves-Silva et al., 2023). Adaptation in implementation can also shift roles and trigger backlash, which may alter accountability and incentives beyond the framework's

assumptions (Kirk et al., 2023). Table (6) summarizes the main threats, their expected impacts, and the mitigations used to bound inference, including sensitivity ranges for idiosyncratic contexts and external holdouts for geographic transfer.

Measurement limitations remain material: rubric miscoding can introduce construct bias, so IRR plus adjudication and 15% dual coding were used, but residual subjectivity is still possible. Misapplication is a second failure mode, especially when recommendations are treated as policy mandates rather than decision aids; misuse guardrails and explicit boundary cues reduce, but do not eliminate, this risk. Future work should strengthen people-centric participation measures and expand empirical validation across contexts (Mathew & Bangwal, 2024).

Table 6. Limitations and mitigations

Limitation	*Impact*	*Mitigation*	*Boundary Cue*
Cohort omits local nuance	Lower internal validity	Sensitivity ranges	Idiosyncratic contexts
Transfer to new areas	Lower external validity	External holdouts	New geographies
Rubric miscoding risk	Construct measurement bias	IRR plus adjudication	15% dual coding
Recommendations misapplied	Harmful policy action	Misuse guardrails	Unsafe practice cue

Failure Modes, Misuse Guardrails, and External Validity Holdouts

Failure modes in urban WASH PPPs often arise when partnership instruments are adopted rapidly without statutory, financial, and institutional enabling frameworks, which can convert PPPs into a vehicle for deferred maintenance and fiscal leakage rather than service improvement (Mutandwa & Vyas-Doorgapersad, 2023). Misuse risk also follows commercialization logics that privilege debt servicing and full cost recovery, potentially excluding non-bankable projects and widening unequal access (Heckel, 2023). Limitations include residual sensitivity to local political economy conditions that are not fully represented in programmatic cohorts.

Fig. (6) maps how these risks translate into guardrails and into external validity holdouts intended to surface context dependence. Guardrails emphasize culturally grounded partnering, clear decision rights, and community sovereignty, since misaligned values and asymmetric control can derail co-produced infrastructure even when finance is available (Pool et al., 2023). Boundary conditions include applicability to urban WASH PPP decision support under documented constraints; claims are not intended to substitute for site-specific engineering design or procurement detail.
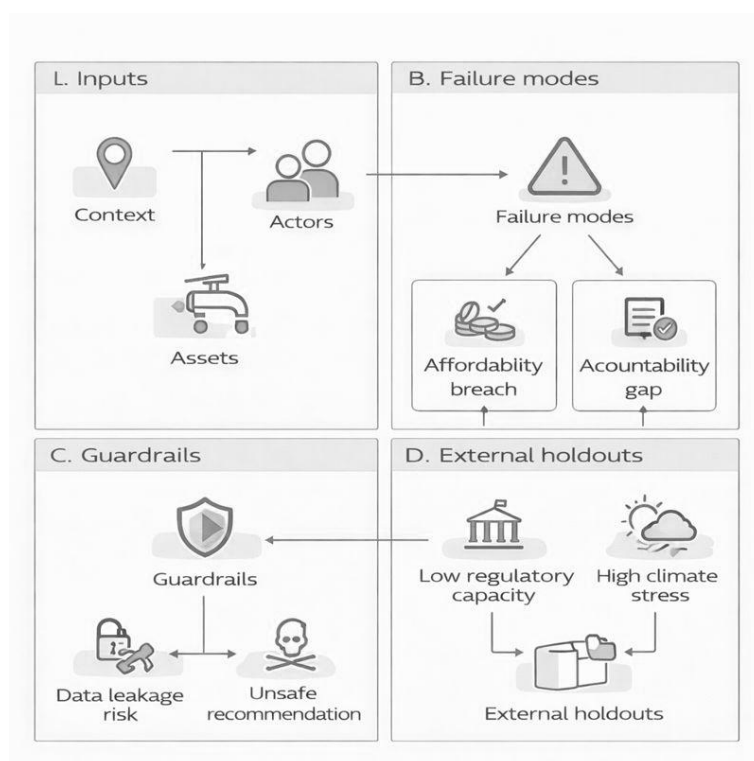
Figure 6. *Misuse guardrails and failure modes*

Conclusion

The proposed model links urban WASH PPP context to decision rules that prioritize reliability, affordability, equity, and accountability. Its emphasis on provider functionality and explicit pro-poor provisions aligns with enabling-environment patterns observed across diverse cities (Trimmer et al., 2023). The accompanying rubric matters for inclusive service delivery because it reduces

discretionary interpretation and makes assumptions traceable. Generalization remains bounded by institutional capacity and local political economy, so decision outputs should be treated as contingent rather than prescriptive. Beyond case-specific guidance, the framework also clarifies process elements that shape sustainable-city PPP performance, including governance arrangements, public-private-people partnerships, sustainability objectives, and innovation pathways (Leshinka et al., 2023). Evaluability is retained through measurable indicators and acceptance criteria, enabling empirical audits under grouped holdouts and stress tests when such data are available. Plausible failure modes include miscoding of constructs and transfer limits to new geographies; these risks underscore the need for transparent provenance and periodic recalibration.

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