Integrated Urban WASH Planning: Bridging Informal Settlements and Formal Infrastructure

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Abstract: *This study presents an operational conceptual model for integrated urban Water, Sanitation and Hygiene (WASH) planning that links informal-settlement context to portfolio decisions under resource, affordability, and governance constraints. Current practice often relies on fragmented decision logics and incomplete data, leaving limited basis for comparing sewer-first masterplans, water-only expansion, and data-driven ranking under identical conditions. The proposed framework specifies core constructs and mechanisms, then translates them into evaluable propositions using a programmatic cohort grounded in public aggregate WASH statistics and utility key performance indicators (KPIs). Validation is specified through grouped holdouts and external holdouts, baseline comparisons, and uncertainty reporting using BCa bootstrap with 2000 resamples and 10 seeds, with multiple testing controlled using FDR at alpha 0.05; rubric labels are planned from two annotators on a 15% sample with adjudication. Primary decision outcomes are operationalized as equity adjusted coverage (percent), affordability stress index (dimensionless), and cost per new household USD (USD), with acceptance criteria including equity adjusted coverage meets >=70 with 95% CI and affordability stress index meets*

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<=1.0 with 95% CI, while empirical performance results are not reported here. The framework provides a practical basis for utilities, municipalities, and settlement leaders to select and audit WASH upgrading pathways when household-level targeting and site-specific engineering detail are out of scope.

Keywords: Integrated Urban WASH Planning, Informal Settlement Upgrading, Participatory Governance, Decision-Support Framework, Programmatic Cohort Validation, Equity-Adjusted Coverage, Affordability Stress Index

Introduction

Inclusive urban planning increasingly confronts intertwined demands for social justice, climate resilience, and sustainable growth, yet water and sanitation deficits remain persistent constraints in many cities (Cheshmehzangi, 2025; Kiptum et al., 2023). Governance responses in informal settlements often overlook migrant and community perspectives, which can weaken adaptation planning under climate hazards (Tietjen et al., 2023). Fig. (1) grounds the analysis in a plausible planning setting where informal neighbourhoods and formal infrastructure interact under resource limits.

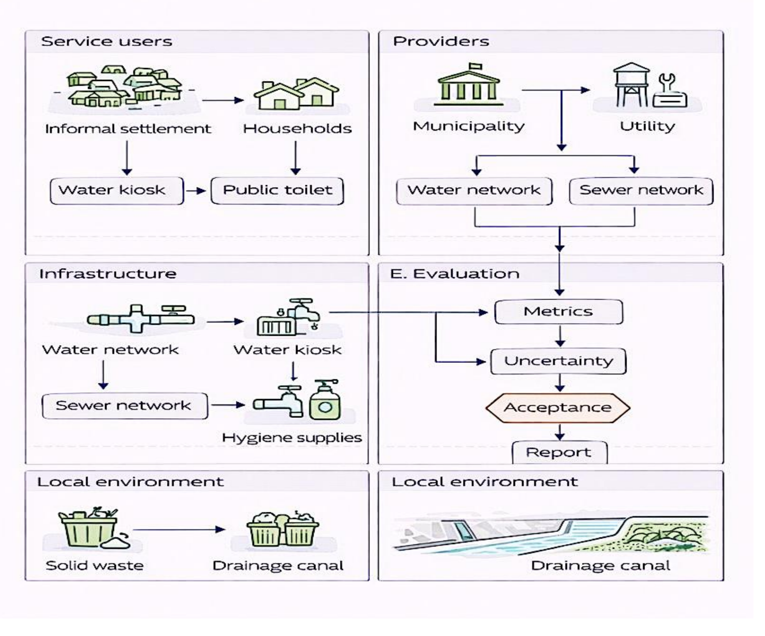

Figure 1. *Urban WASH planning domain scene*

Equity and water-justice concerns motivate an explicit focus on who gains service improvements, at what cost, and under which institutional arrangements (Mukherjee & Sundberg, 2023). Research design transparency is preserved by framing the contribution as a conceptual model and theory synthesis: core constructs are specified, relationships are expressed as mechanisms rather than diagrams, and evaluable propositions are formulated for subsequent validation using public aggregate WASH statistics in grouped holdouts. Some implementation details of that validation are not reported here.

Background and Related Foundations

Inclusive governance in technology-driven cities is often constrained by centralized planning and weak regulatory capacity, which limits community-level action even when digital infrastructure is available for service delivery in informal settlements (Al-Saidi & Zaidan, 2024; Sha et al., 2024). Prior reviews on inclusion underscore that disadvantaged groups, including persons with disabilities, remain marginal in smart-city agendas, and technical fixes rarely address structural exclusion (Makkonen & Inkinen, 2024). Conceptual framings such as City 4.0 broaden evaluation beyond efficiency by linking societal, environmental, and economic objectives (Yiğitcanlar et al., 2023).

Planning scholarship also emphasizes that outcomes depend on interactions among actors rather than on formal institutional design alone, a pattern visible in analyses of city networks for climate- and energy-responsive planning (Santopietro & Scorza, 2024). Practice-oriented frameworks such as the 15-minute city illustrate how spatial accessibility goals can be translated into policy guidance, albeit with context specificity (Shoina et al., 2024). Evidence on sanitation entrepreneurship remains fragmented; a Scopus-based bibliometric review mapped 375 papers and highlighted uneven thematic attention (Kumar et al., 2023).

WASH Baselines: Sewer-First Masterplans and Linear Scoring Models

Credible evaluation in inclusive urban WASH planning depends on baselines that encode common decision logics. Table (1) summarizes four alternatives: Linear Scoring Rank, Gradient Boosted Rank, Sewer-First Masterplan, and Water-Only Expansion, together with their decision logic, key assumption, and a failure-mode cue. For baselines, the linear and boosted rankings assume transferable weights or sufficient training data, whereas sewer-first planning assumes centralized feasibility and can bind on affordability; water-only expansion leaves sanitation lag and persistent risk (Shulajkovska et al., 2024).

Comparison on explicit axes reduces the risk of attributing performance differences to modeling style alone. Fig. (2) contrasts sewer-first and scoring baselines across feasibility, data dependence, and sensitivity to context shift. The benchmark protocol follows prior decision-support comparisons in Shulajkovska et al. (2024) but is adapted to portfolio selection under policy limits and aggregate statistics. A practical implication is evaluability: failures predicted by context shift bias or affordability constraints can be checked using grouped holdouts and scenario stress tests (Shulajkovska et al., 2024).

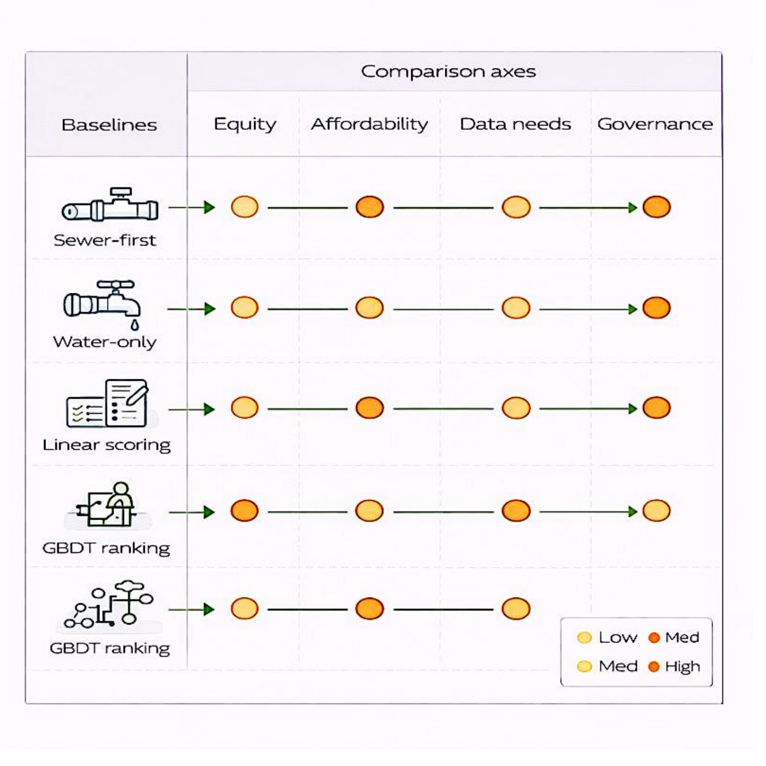

Figure 2. *Baseline approaches and comparison axes*

Table 1. Baselines and key assumptions

Baseline Approach	*Decision Logic*	*Key Assumption*	*Failure Mode Cue*
Linear Scoring Rank	Weighted sum ranking	Stable weights transfer	Context shift bias
Gradient Boosted Rank	Nonlinear ranking model	Sufficient training data	Overfit under shift
Sewer-First Masterplan	Network expansion first	Centralized sewer feasible	Affordability constraint binds
Water-Only Expansion	Water supply prioritized	Sanitation can lag	Health risk persists

Evidence Corpus for Public WASH Statistics and Utility KPIs

The evidence corpus integrates public WASH statistics, indicator ladders, utility key performance indicators (KPIs), and rubric-based labels to parameterize the Inclusive Urban WASH Upgrading Pathways Cohort under public, aggregate constraints. Evidence corpus integrity is protected by explicit inclusion and exclusion rules and a documented provenance chain. Fig. (3) documents the screening logic and provenance links for all public sources, reducing cherry-picking risk. Community-sourced collection remains defensible when tools structure contributions and preserve traceability (Jiménez-Caldera et al., 2024).

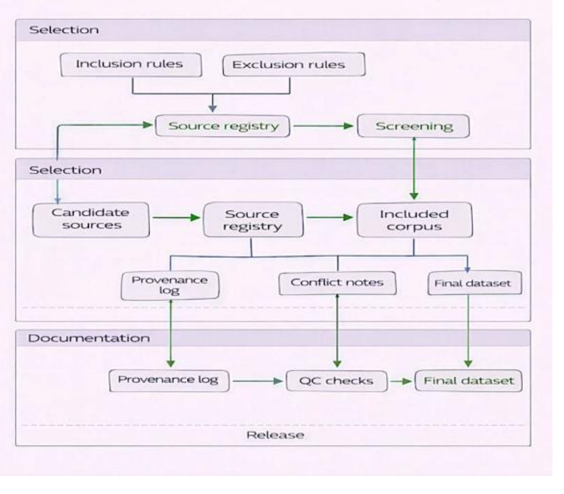

Figure 3. *Evidence selection and provenance flow*

Table (2) lists each source type with paired integrity and leakage controls, together with lineage artifacts (manifest_sha256.txt, config.yaml, split_hashes.json, seed_log.csv) that permit auditability. Range checks constrain public statistics and ladder codings, while grouped holdouts, pre-committed windows, and entity ID splits limit cross-context contamination. For rubric labels, two annotators coded a 15% sample with adjudication to manage disagreement. Multilevel covariates are retained to separate individual and regional drivers in downstream analysis (Kim & Kim, 2024).

Table 2. Evidence sources and lineage controls

Source Type	*Example Use*	*Integrity Control*	*Leakage Control*	*Lineage Artifact*
Public WASH stats	Cohort parameters	Range checks	Grouped holdouts	manifest_sha256.txt
Indicator ladders	Service level coding	Range checks	Pre-committed windows	config.yaml
Utility KPIs	Operator constraints	QC blockers	Entity ID splits	split_hashes.json
Rubric labels	15% coded sample	Two annotators	Adjudication	seed_log.csv

Conceptual Framework

The proposed framework treats participatory water, sanitation, and hygiene (WASH) planning as decision-support infrastructure that organizes information, deliberation, and accountability across actors and jurisdictions. This stance aligns with participatory action research platforms that couple analytic tools with real-time citizen input to support municipal choices (Meza et al., 2024). For informal settlements, the emphasis shifts from single projects to portfolios that can be compared under explicit constraints. Decision support is therefore positioned as a governance asset, not only a technical aid.

Urban experiments offer a complementary logic: interventions are trialed, monitored, and revised while participation is negotiated in practice rather than assumed (Treija et al., 2023). The analysis emphasizes mechanisms that commonly condition collaboration, including communication quality, balance of interests, and the degree of resident influence on decisions. In the WASH setting, these mechanisms motivate iterative selection of upgrading pathways, followed by cohort-based checks using equity adjusted coverage, affordability stress index, and cost per new household USD. Applicability remains bounded by institutional capacity and the availability of public aggregate statistics.

Key Constructs and Definitions for Equity-Adjusted Coverage Decisions

Core constructs were defined to support consistent coding in constrained informal-settlement WASH decisions, drawing on characterization frameworks (Bakhaty et al., 2023). Fig. (4) standardizes the units of analysis and the coding vocabulary used across cities. Equation (1) defines Equity-Adjusted Coverage (EAC) as 100 times the equity-weighted mean of coverage c_i under weights w_i. Enabling-environment and social-network constructs were operationalized to remain comparable across governance settings (Love et al., 2022). This explicit metric definition strengthens conceptual precision and limits ambiguous interpretation.

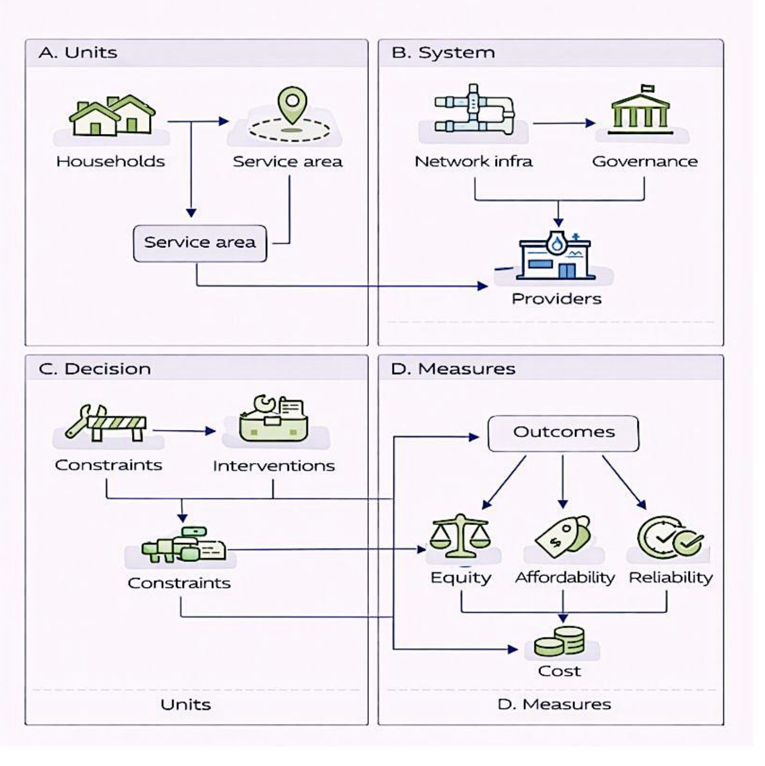

Figure 4. *Core constructs, units, and definitions*

Equation (2) maps vulnerability v_i to equity weights w_i via an exponential function governed by lambda, making the weighting rule inspectable. Table (3) defines each construct alongside an operational indicator, including affordability stress index, cost per new household USD, and a Leave-Group-Out check for cross-city transfer. Housing and social sustainability concepts motivate attention to affordability and community effects, but remain bounded to measurable proxies in the cohort (Ziaesaeidi & Farsangi, 2024). Together, the definitions reduce slippage between narrative claims and decision rules during portfolio appraisal.

$$EAC = 100 \frac{\sum_{i=1}^{N} w_i \ c_i}{\sum_{i=1}^{N} w_i} \quad (1)$$

$$w_i = exp(\lambda \, v_i) \quad (2)$$

Table 3. Construct definitions and indicators

Construct	*Definition*	*Operational Indicator*
Equity-Adjusted Coverage	Coverage weighted by equity	Equity adjusted coverage (%)
Affordability Stress	Affordability under constraints	Affordability stress index
Cost Per New Household	Unit cost per household	Cost per new household USD
Cross-City Transfer	Generalization across cities	Leave Group Out check

Boundary Conditions Across Informal Settlements, Affordability Caps, Governance

Boundary conditions are made explicit to prevent over-generalizing from documented service deficits in informal settlements. Table (4) enumerates where the framework applies and where it can fail, including reliance on public aggregate data that supports only aggregate statistics and therefore cannot enable household-level targeting (Adamu et al., 2025; Hossain & Sultana, 2023). Validity of grouped holdouts also depends on stable entity identifiers; if identifiers are reused across splits, leakage risk increases and apparent cross-city transfer can be overstated.

Affordability constraints are operationalized through the Affordability Stress Index (ASI), which compares the summed expected payments to the summed affordability caps across the analysed units; Equation (3) defines this ratio. The affordability-caps assumption holds when tariffs and fee structures constrain costs, but it fails when caps are politically or administratively non-binding, rendering recommended portfolios budget-infeasible. Comparable caution applies to operator capacity limits and scenario-based climate or growth stress, which can shift outcomes beyond single-settlement evidence (Adamu et al., 2025).

$$ASI = \frac{\sum_{i=1}^{N} p_i}{\sum_{i=1}^{N} A_i} \quad (3)$$

Table 4. Boundary conditions and applicability limits

Boundary	***Applies When***	***Fails When***	***Impact Cue***
Public aggregate data	Only aggregate stats	Individual linkage needed	No household targeting
Grouped holdouts	Entity IDs stable	IDs reused across splits	Leakage risk
Affordability caps	Tariffs constrain costs	Cap assumptions invalid	Budget infeasible
Operator capacity limits	Response time bounded	Capacity unmodeled	Reliability over-claimed
Climate and growth stress	Scenarios pre-set	Unmodeled hazard shift	Robustness unknown

Causal Mechanisms Linking Governance and Service Reliability Outcomes

Governance differences are treated as upstream determinants of how WASH portfolios are selected, implemented, and maintained across heterogeneous urban areas, consistent with spatially differentiated renewal typologies in (Zuo et al., 2024). Fig. (5) formalizes the causal logic and mechanisms by linking governance unit type to levers such as participation and coordination, and by stating the core assumptions required for identification of these pathways. The intent is not prediction, but a transparent map from institutional choices to service reliability outcomes.

Table (5) maps five mechanism pathways to intervention levers and expected outcome shifts, anchoring the causal logic and mechanisms in observable service metrics. Participatory co-planning and cross-agency coordination are posited to reduce blind spots and raise reliability through improved equity coverage, while affordability constraints and operator capacity bounds target cost overrun and maintainability via affordability index and response-time limits. Stress-tested robustness highlights when choices should transfer under holdout transfer, extending insights from (Zuo et al., 2024).

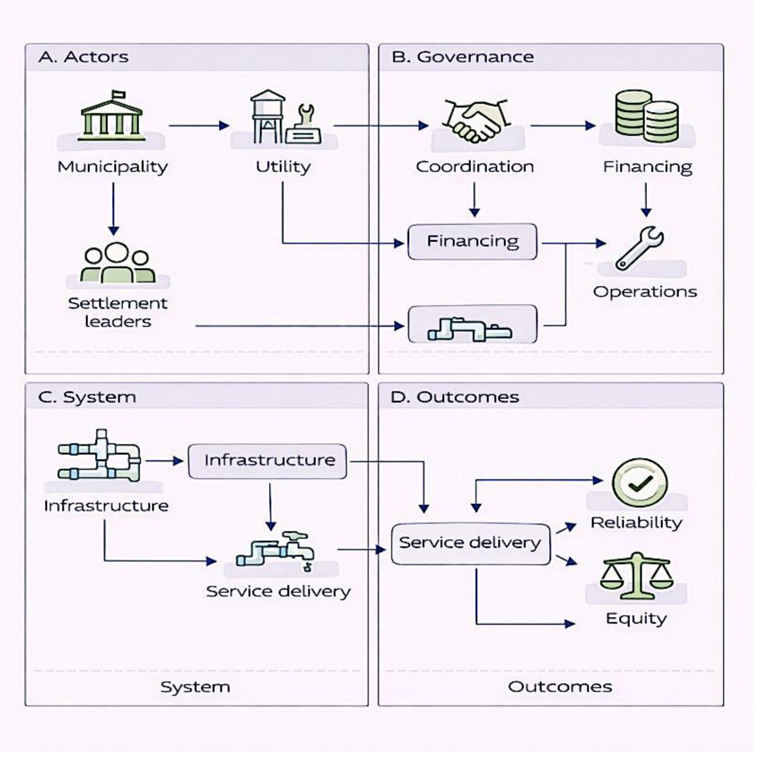

Figure 5. *Mechanism linking governance to outcomes*

Table 5. Mechanisms and expected effects

Mechanism	*Intervention Lever*	*Expected Outcome Change*	*Primary Metric Link*
Participatory co-planning	Citizen data tools	Fewer blind spots	Equity coverage
Cross-agency coordination	Integrated portfolio	Higher reliability	Equity coverage
Affordability constraints	Cost caps encoding	Less cost overrun	Affordability index
Operator capacity bounds	Response-time limits	Better maintainability	Equity coverage
Stress-tested robustness	Resource and climate tests	More stable choices	Holdout transfer

Propositions and Implications

The proposed framework advances integrated urban WASH decision support by linking contextual constraints to portfolio choices, rather than defaulting to a sewer-first masterplan or water-only expansion without sanitation integration. It further posits that data-driven ranking models should outperform linear scoring for project prioritization when heterogeneity across settlements is material. The causal logic is that aligning water and sanitation investments removes binding service constraints, which otherwise dilute equity-adjusted coverage gains. Affordability stress can shift the preferred sequence.

These propositions are evaluable using equity_adjusted_coverage, affordability_stress_index, and cost_per_new_household_USD, complemented by cross_city_transfer_check, scenario_drift, and slice_analysis in grouped holdouts. Stress tests under resource and climate constraints are expected to reveal where recommendations fail. No individual-level health claims are implied. Alternative explanations, such as governance capacity dominating technical portfolio effects, remain plausible and should be distinguished empirically; detailed construct definitions and evidence selection rules are not reported here. Transfer to new geographies may vary, and cost acceptance criteria are unspecified.

Testable Propositions H1-H2 Using Grouped Holdouts and External Holdouts

Testable propositions H1-H2 are assessed using grouped holdouts and external holdouts so that claims remain falsifiable across heterogeneous urban contexts. Fig. (6) lays out the evaluation blueprint linking each proposition to observable service outcomes and explicit acceptance criteria. Evaluability is strengthened by requiring consistent indicators for coverage, affordability, and cost, rather than narrative plausibility alone. Evaluation is halted if the leakage audit fails. Grouped and external partitions separate geography and governance regimes, limiting overfitting to a single city.

Table (6) specifies leave-group-out splits, primary metrics (coverage, affordability, cost), and baselines that pair ranking with planning, with success defined as beating the baselines in holdouts. Uncertainty is quantified with BCa bootstrap and reported as 95% CI at alpha 0.05, supporting decision rules that can be directly audited. Equation (4) defines the grouped-holdout gain as the median difference between the model and baseline across groups for each metric.

$$\Delta_m = median_{g \in G}\left(m_{model,g} - m_{baseline,g}\right) \quad (4)$$

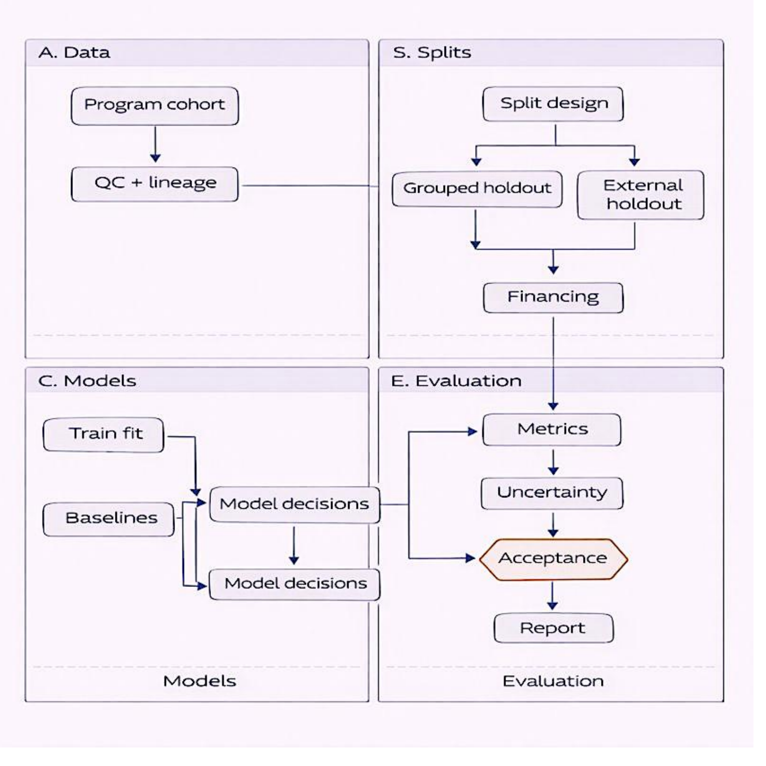

Figure 6. *Holdouts, metrics, and acceptance criteria*

Table 6. Validation protocol summary

Element	*Specification*	*Acceptance*
Splits	Grouped holdouts	Leave-group-out
Primary Metrics	Coverage, affordability, cost	Meets AC1-AC3
Baselines	Ranking plus planning	Beat in holdouts
Uncertainty	BCa bootstrap	95% CI, alpha 0.05
Leakage Controls	Train-only fit	Leakage audit pass

Alternative Explanations: Water-Only Expansion Versus Integrated Sanitation

Integrated WASH planning can be framed as an infrastructure-led design problem rather than a sequence of sectoral upgrades, which motivates comparing water-only network expansion with sanitation-integrated portfolios. Drawing on the orientation that treats infrastructure as a primary design element within neighborhood planning, integrated sanitation is expected to reduce rework and improve service continuity when streets, drainage, and utilities are co-planned (Choi, 2024). The contrast clarifies which design choice is presumed to drive equity and affordability gains.

Plausible alternative explanations remain. Coverage improvements may arise from water-only expansion if supply reliability is the binding constraint, while sanitation integration may appear beneficial mainly because it proxies for stronger municipal coordination and capital access. These alternative explanations imply different observable patterns: water-only projects should raise equity_adjusted_coverage without consistent changes in affordability_stress_index, whereas integrated portfolios should shift both and lower cost_per_new_household_USD through shared works. Empirical discrimination is not reported here, but the logic follows infrastructure-as-design arguments (Choi, 2024).

Robustness Stress Tests Under Resource and Climate Constraints

Feasibility under binding implementation constraints is treated as a first-order design requirement for the proposed urban WASH decision support, not an afterthought. Lessons from deployment-oriented frameworks in underserved communities emphasize that infrastructure readiness, financing pathways, privacy and governance constraints, and sustained community engagement often dominate technical merit (Nwokediegwu & Ugwuanyi, 2024). To support robustness of reasoning, the argument is stress-tested against resource scarcity (capital, staff time, data) and climate shocks, noting that empirical stress-test outcomes are not reported here.

Stress-test assumptions focus on contexts where service coverage gains compete with affordability and operational fragility. Guided by Nwokediegwu & Ugwuanyi (2024), edge cases include low-connectivity settlements, intermittent power for monitoring, and policy shifts that limit data sharing or tariff reforms. Relaxing assumptions about stable budgets, institutional capacity, or climate stationarity can change which intervention portfolios remain feasible, even when equity_adjusted_coverage improves. These sensitivities motivate grouped holdouts and scenario_drift checks, but the results are not reported here.

Limitations and Future Work

Limitations arise from the evidence base and the level of abstraction of the proposed framework. Context-specific living-lab insights can clarify mechanisms of social learning, yet they rarely yield transportable effect sizes, which constrains inference beyond the studied setting (Blezer et al., 2024). Likewise, planning case comparisons often depend on local political economy and ecological histories, so direct transfer of decision rules across cities remains uncertain (Simons et al., 2023; Zingraff-Hamed et al., 2022). Public aggregate statistics may also mask intra-settlement heterogeneity.

Future work should improve evaluability by operationalizing constructs, documenting coding guidance, and testing propositions against grouped holdouts in the programmatic cohort. Deployment risks warrant governance: embedded sensing and automation for sanitation may fail through maintenance gaps or inequitable access, even when technically feasible (Gude et al., 2024). Urban AI ethics principles can guide misuse checks, privacy safeguards, and accountability in municipal settings (Hendawy & Ghoz, 2024). Transfer checks should sample additional planning domains, including local housing strategies, to clarify boundary conditions (Álves et al., 2023).

Conclusion

The present study develops an operational conceptual model for inclusive urban WASH planning that links settlement context to intervention portfolio choices and measurable service outcomes. Relative to sewer-first masterplans, water-only expansion, and purely model-based project ranking, the framework integrates sanitation and water decisions with equity-adjusted coverage, affordability stress, and cost per new household. The emphasis is on comparability across cities and governance settings, rather than site-specific engineering design. Evaluability is maintained through a programmatic cohort grounded in public aggregate WASH statistics, with grouped holdouts by geography and context, leakage audits, and preprocessing fit on training data only. Uncertainty is planned via BCa bootstrap confidence intervals with 2000 resamples and 10 seeds, and multiple testing is controlled using FDR at alpha 0.05. The approach may still miss local idiosyncrasies, depends on accurate construct coding, and excludes individual-level outcomes and clinical trials.

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