Designing Climate Smart WASH Infrastructure for Flood-Prone Rural Areas

Deepak N. Kakade, Prashant Anerao, Samir N. Ajani, Kiran Panditrao Shejwal, Rutuja Pandit Mhaske, Mihir Hasmukh Devikar

Abstract: *This study presents a conceptual decision framework for flood-resilient rural water, sanitation, and hygiene (WASH) services that links hazard zoning to design packages, governance capacity, and operations and maintenance requirements. Existing practice commonly separates hazard mapping, engineering design, and governance checklists, which limits traceable package selection under sparse monitoring and disrupted access. The framework is derived through theory synthesis and reconciliation of guidance and resilience sources, with inclusion and provenance rules that keep decisions auditable; empirical validation is not reported here. It defines a flood-season service continuity index (0-1) and component metrics for water uptime, sanitation functionality, contamination incidents (per 1000 user-days), and lifecycle cost ratio. Thresholds encode acceptability: Continuity Index >= 0.80 (95% CI), Water Uptime >= 90%, Sanitation Functionality >= 85%, Worst-Slice Continuity >= 0.65, and Lifecycle Cost Ratio <= 1.10. The evaluability plan uses grouped and seasonal holdouts, bootstrap intervals, calibration checks, and halt rules that default to conservative packages when inputs are missing for implementers in flood-prone rural communities.*

Keywords: Water, Sanitation, and Hygiene (WASH), Flood Hazard Zoning, Rural Service Continuity Index, Decision Thresholds and Constraints, Governance

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Capacity Metrics, Operations and Maintenance Planning, Non-Sewered Sanitation Chains, Contamination Risk Indicators

Introduction

Flood-prone rural water, sanitation, and hygiene (WASH) services face coupled hazard, infrastructure, and governance failures that are often treated as isolated checklists. A systems-thinking review of flood risk management reports slow uptake of integrated framing, with 11.61% annual growth and a pronounced developing-country gap (Awah et al., 2024). This study targets decisions that remain traceable under sparse monitoring, limited access, and tight budgets. Fig. (1) anchors the proposed decision framework in a representative rural WASH service setting during flood season.

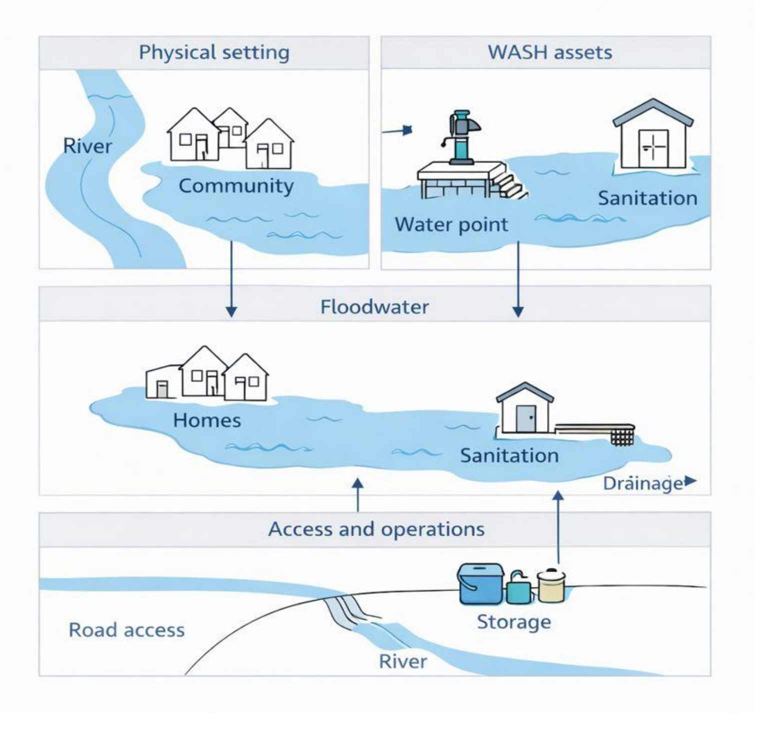

Figure 1. *Flood season rural WASH context scene*

The theoretical contribution is an integrative decision framework that links hazard zoning, design packages, governance capacity, and operations and maintenance metrics without implying empirical validation (Awah et al., 2024). Parsimony and scope discipline are enforced by restricting applicability to flood-prone rural, non-sewered sanitation chains and by excluding fully sewered urban systems and real-time control. Research design transparency is pursued through synthesis and analytic derivation from prior evidence, although the stepwise selection and reconciliation rules are not reported here.

Background and Related Foundations

Flood risk decisions for rural WASH are often anchored to mapped floodplains, yet exposure and inequities can be missed by regulatory maps. Community-scale floodplain development indexes quantify how settlement growth intersects hazard zones and reveal heterogeneous drivers (Agopian et al., 2024). Advanced flood modeling further indicates large populations residing in federally overlooked 100-year floodplains, with income-linked disparities across flood types and urban-rural settings (Flores et al., 2025). Spatiotemporal analyses of risk and resilience evolution motivate non-stationarity assumptions when translating past patterns to future seasons (Chen et al., 2024).

Urban flood resilience indices illustrate indicator selection and weighting choices, including TOPSIS-based systems and correlation-aware schemes (Ji et al., 2024; Li et al., 2024). Standardized resilience frameworks for water services aim for comparable yet flexible scoring, informing the proposed taxonomy for rural WASH continuity (Barreiro et al., 2024). Vulnerability index concepts stress multi-domain drivers, but also expose proxy drift when indicators detach from service outcomes (Borowska-Stefańska, 2024). Integration and synthesis logic aligns these strands with design-for-failure governance perspectives (Huang & Wang, 2024). Evidence corpus integrity and baselines are considered, but inclusion rules are not reported here.

Evidence Corpus Rules for WASH Standards and Resilience Frameworks

Evidence corpus integrity was protected by pre-specifying inclusion and exclusion rules for guidance and planning documents, adapting plan-quality lessons that emphasize explicit exposure and implementable guidance (Roy et al., 2024). Table (1) summarizes inclusion rules and provenance logging for each source type. Sources were included only when they defined WASH terms, resilience metrics, or operational methods; anecdotal guidance, vague definitions, and unvalidated black-box approaches were excluded. Each retained item required a traceable provenance record.

Research design transparency was maintained by logging scope, assumptions, and audit trails so that later readers can reconstruct why a document informed hazard zoning, governance metrics, or measurement protocols. Fig. (2) documents the flow from candidate-source screening to provenance checks and final corpus entry. Integration and synthesis logic followed a mapping rule: only sources with operational definitions were allowed to anchor construct alignment, reducing jingle-jangle risks noted in plan networks (Roy et al., 2024).

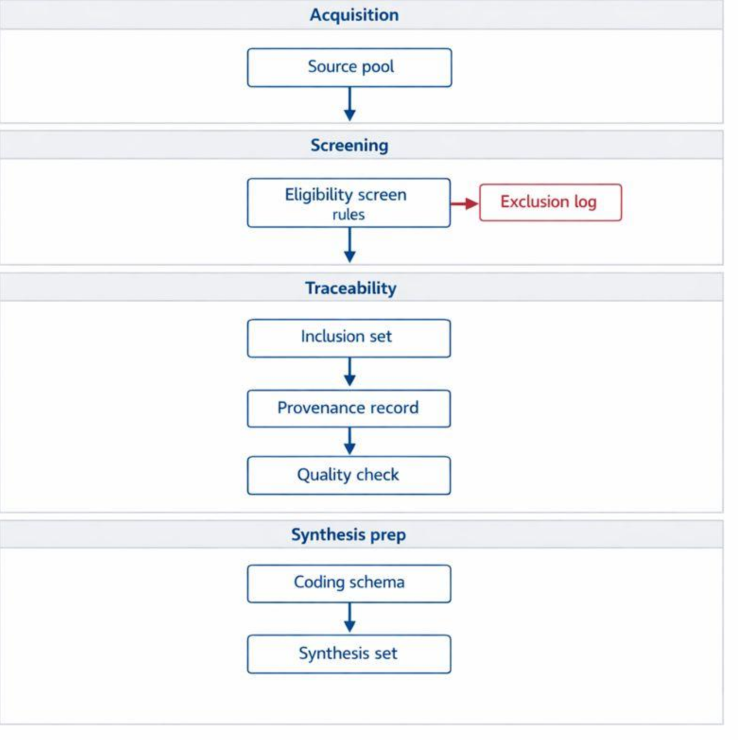

Figure 2. *Evidence corpus selection and provenance*

Table 1. Evidence corpus rules summary

Source Type	***Include Rule***	***Exclude Rule***	***Provenance Log***
Guidance standard	Defines WASH terms	Anecdotal guidance	Version plus date

Resilience framework	Defines resilience metrics	Vague definitions	Scope and assumptions
Hazard zoning method	Explicit zoning rules	Unvalidated black box	Inputs and maps
Governance toolkit	Operational governance metrics	Non-operational checklist	Indicator mapping
Measurement protocol	Defines observation sources	Undefined data origin	Audit trail record

Construct Genealogy Across Hazard Zoning and Rural WASH Continuity

Construct genealogy and alignment is anchored in interdependence-aware post-hazard functionality, where service outcomes depend on utilities and access rather than on asset condition alone (Nofal et al., 2024). The present study carries that logic into hazard zoning by treating zones as constraints on exposure, access, and repair feasibility across the rural WASH service chain. Conceptual precision is maintained by reserving functionality for component operating states and continuity for time-aggregated service delivery during the flood season.

Internal consistency and coherence requires that zoning triggers map to mechanisms, not to labels, so that a high-hazard zone implies specific failure pathways (inundation, road cut-off, power loss) that can cascade into water and sanitation interruption (Sett et al., 2024). Mechanism language is therefore harmonized with impact-chain and impact-web representations to keep dependencies explicit and to avoid jingle-jangle drift across sectors (Nofal et al., 2024; Sett et al., 2024). Empirical adequacy is not claimed here; the value is a traceable alignment for later testing.

Conceptual Framework

The conceptual framework adapts community resilience measurement constructs to flood-resilient rural WASH decisions, using Flood Resilience Measurement for Communities (FRMC) as a reference vocabulary (Paszkowski et al., 2023). Conceptual precision is maintained by treating hazard zoning as the exposure context, design packages as the physical service-chain response, and governance capacity as the enabling condition for operation and maintenance.

Absorptive capacity is aligned with routine coping and redundancy, whereas transformative capacity is aligned with institutional change and financing reform (Paszkowski et al., 2023).

Internal consistency and coherence are enforced by a single mechanism: comparable hazard intensity produces different continuity outcomes when governance supports timely maintenance, supply logistics, and rule compliance. Fig. (3) links hazard, design, and governance constructs to continuity, functionality, contamination risk, and lifecycle cost ratio, avoiding level-of-analysis slippage. Assumptions and foundational commitments are explicit: decisions prioritize service continuity and safety, treat governance as a moderator rather than a substitute for design, and remain conceptual without empirical validation here (Paszkowski et al., 2023).

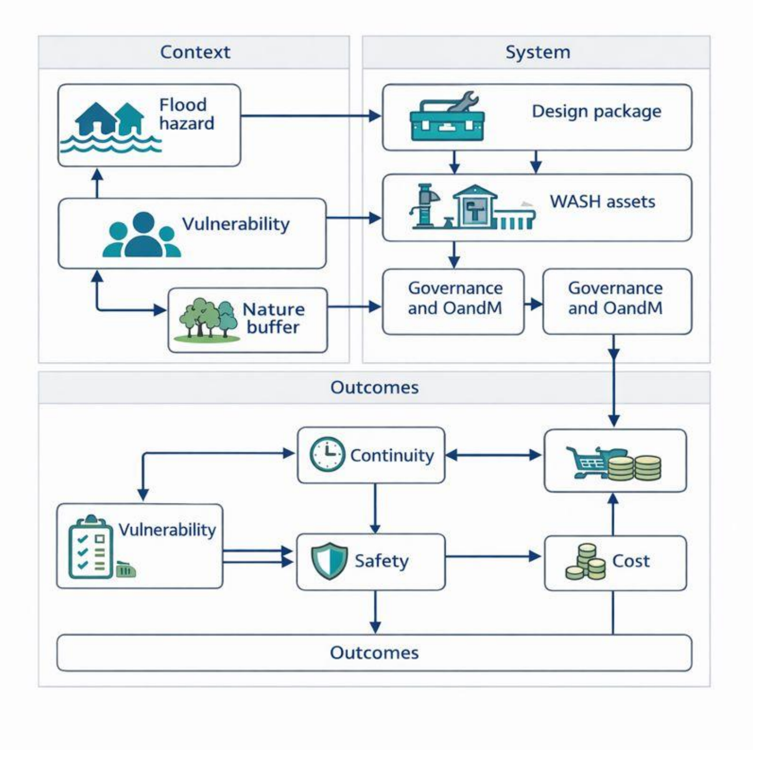

Figure 3. *Integrated constructs and mechanism map*

Key Constructs and Definitions for Risk Zone Class Packages

Risk-zone class packages are grounded in constructs linking flood susceptibility, governance-related exposure, and service-chain performance (Prall et al., 2024). Construct genealogy and alignment draws on GIS-index workflows for flood risk zoning (Efraimidou & Spiliotis, 2024; Wu & Jiang, 2024) and contrasts fuzzy vs AHP susceptibility pipelines to make design choices explicit (Sayadi et al., 2025; Wu & Jiang, 2024). Equation (1) defines the continuity index as a weighted sum, supporting conceptual precision by tying package choice to continuity, function, and safety rather than a single proxy.

Table (2) lists the constructs, metric definitions, units, and missingness rules used in the risk-zone scoring package. For metric definition, Water Uptime is 1 - outage share (Percent (%)). Planned downtime is excluded, and outages are logged. Contamination Incidents counts exceedances per exposure (Per 1000 user-days) and flags proxy measures for sensitivity. Lifecycle Cost Ratio is Package / status-quo cost (Ratio (x)) and triggers a halt if inputs are missing, aligning implementation with public-data scoring baselines (Peixoto et al., 2024) and multi-component vulnerability indices (Ali et al., 2023).

$$C = \sum_{j=1}^{3} w_j \ m_j \tag{1}$$

Table 2. Constructs and metric definitions

Construct	***Metric Definition***	***Unit***	***Missingness Rule***
Flood-Season Continuity	Weighted uptime, function, safety	Index (0-1)	Penalty; flag missing
Water Uptime	1 - outage share	Percent (%)	Log; exclude planned
Sanitation Functionality	Units meeting criteria	Percent (%)	Audit; report CI95
Contamination Incidents	Exceedances per exposure	Per 1000 user-days	Flag proxies; sensitivity
Lifecycle Cost Ratio	Package / status-quo cost	Ratio (x)	Halt if inputs missing

Boundary Conditions for Flood Season Non-Sewered Service Chains

Boundary conditions define where the flood-season framework for non-sewered rural service chains is expected to hold and where it fails. Table (3) enumerates exclusions, including centralized sewers, infeasible operations and maintenance (O&M) access, absent monitoring, full population displacement, and settings that demand continuous telemetry rather than an offline checklist. These limits align the framework with built-environment constraints reported in prior syntheses of flood impacts on housing and services (Chohan et al., 2024).

Parsimony and scope discipline is maintained by treating nature-based buffers as optional adaptations rather than default requirements; modelled benefits can coexist with residual risk and persistent losses, so buffers cannot substitute for basic service-chain feasibility (Narendr et al., 2024). Actionability and misuse risk are addressed by using the listed failure modes as explicit stop rules: when monitoring is absent or displacement is total, the framework should not be used for fine-grained prioritization. Evidence remains context dependent (Chohan et al., 2024; Narendr et al., 2024).

Table 3. Boundary conditions and exclusions

Boundary	*Applies When*	*Fails When*
Non-sewered rural chain	Non-sewered sanitation	Centralized sewers
O&M feasibility	Community O&M feasible	No access for O&M
Monitoring availability	Auditable logs exist	Monitoring absent
Population displacement	Facilities remain usable	Full displacement
Control and telemetry	Offline checklist workflow	Continuous telemetry needed

Decision Framework: Hazard Zoning to Design Package Selection

Hazard zoning is translated into a design-package decision by a rule-based flow that links zone class, asset criticality, and feasibility checks to an actionable package list. For research design transparency, the present study adapted integrated early warning logic into explicit decision rules that map warning-relevant zones to pre-specified action plans (Haque et al., 2024). Fig. (4) encodes the decision steps, required inputs, and governing constraints to keep the mapping traceable and auditable.

The constraint logic screens packages against lifecycle cost ratio <= 1.10 and against access limits during floods, since disrupted mobility can prevent installation, desludging, and emergency response (Salvo et al., 2025). For actionability and misuse risk, the framework specifies required inputs and an operational halt rule, defaulting to conservative safe packages when zoning inputs are unavailable and avoiding use outside the stated rural, non-sewered scope. Event-triggered updates are motivated by observed planning shifts during major flood disruptions (Haque et al., 2024; Salvo et al., 2025).

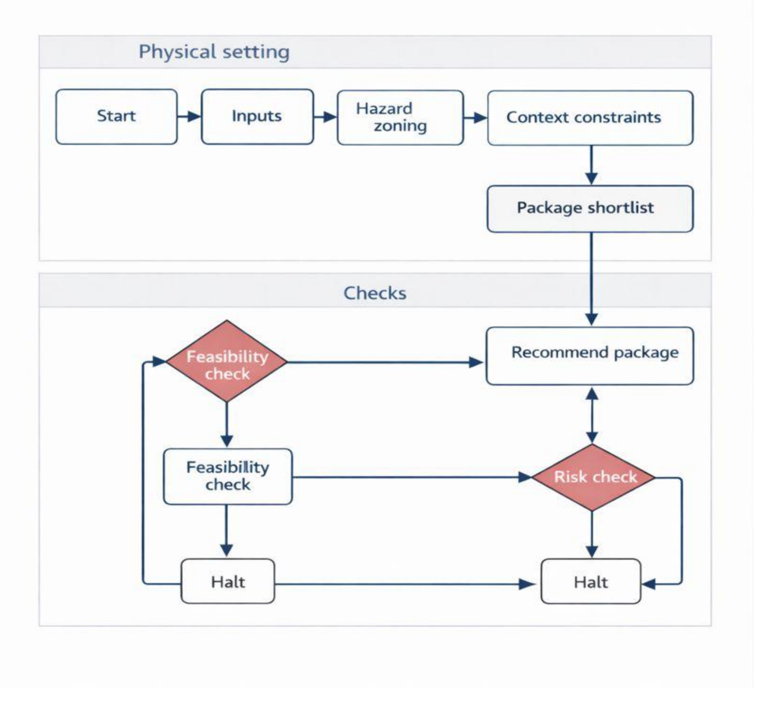

Figure 4. *Hazard zoning to package selection*

Propositions and Implications

Governance-linked propositions are derived for flood-resilient rural WASH by treating plans as a connected system rather than isolated documents. Evidence from planning-network analyses indicates that stronger cross-referencing among plans tends to coincide with higher plan quality and more explicit integration of flood information, which in turn aligns with a greater presence of risk-reducing policies (Meerow et al., 2024). The causal logic and mechanisms in the proposed framework trace governance collaboration capacity to plan connectivity, then to plan quality, and finally to continuity-oriented policy content.

Evaluability is maintained by stating each proposition as a testable association among governance capacity, plan-network connectivity, and the presence of flood-informed, risk-reducing policies (Meerow et al., 2024). For the available data, evaluation could use grouped splits by community or district, a holdout flood season, and grouped bootstrap confidence intervals, with external districts where feasible. Alternative explanations include hazard intensity, fiscal resources, and statutory requirements; these can be probed through stratification or matched comparisons, but such empirical tests are not reported here.

Mechanism Map for Uptime, Functionality, and Contamination Risk

The mechanism map links flood-season outcomes to three upstream drivers: hazard exposure, asset robustness, and governance capacity. Determinant evidence from household and community vulnerability indices indicates that exposure and susceptibility elevate risk, whereas resilience-related resources reduce it (Mwalwimba et al., 2024; Rasool et al., 2024). In causal logic and mechanisms terms, governance affects both maintenance speed and the uptake of protective designs, which in turn shapes downtime and contamination pathways. Internal consistency and coherence are enforced by keeping each link directional and by separating determinants from outcomes.

Preparedness and warning access moderate whether comparable hazards translate into service failure, consistent with survey evidence that forecast access and socio-demographic factors structure preparedness (Rahman et al., 2024). Equity-relevant exposure is treated as a distinct pathway: redlining-linked land-use and hydrologic alterations concentrate flood risk, which can amplify contamination risk even under similar designs (Napieralski et al., 2023). Availability is defined as water uptime percent and sanitation functionality percent over a stated reporting window, distinguishing planned downtime from outages; the operational window is not reported here.

Metrics, Constraints, and Decision Thresholds for Continuity Index

Continuity scoring is anchored in component metrics to reduce proxy drift and to keep weighting schemes transparent, consistent with multi-criteria resilience indices used in flood settings (Estelaji et al., 2024; Zhang et al., 2024). Equation (2) defines flood-season water uptime percent as 100 times (service time minus unplanned outage time) divided by service time. Equation (3) defines contamination exceedances per 1000 user-days as 1000*N_exc/D_user. The units support cross-community comparisons. Missing-data handling is not reported here.

Thresholded decisions translate scores into accept/reject outputs, limiting single-metric dominance under resilience indexing practice (Zhang et al., 2024). Table (4) summarizes cutoffs and sensitivity bands: Continuity Index >= 0.80 with reported 95% CI, Water Uptime >= 90% with a fixed season window, Sanitation Functionality >= 85%, Worst-Slice Continuity >= 0.65 across hazard strata, and Lifecycle Cost Ratio <= 1.10. Equation (4) defines the discounted lifecycle cost ratio as candidate present-value cost divided by baseline present-value cost over horizon H at discount rate r.

$$Uptime = 100\,\frac{T_{service} - T_{out,unplanned}}{T_{service}} \tag{2}$$

$$CIR = 1000\,\frac{N_{exc}}{D_{user}} \tag{3}$$

$$LCR = \frac{\sum_{t=0}^{H} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{H} \frac{C_t^{(0)}}{(1+r)^t}} \tag{4}$$

Table 4. Thresholds and constraints summary

Element	*Threshold Or Constraint*	*Rationale Cue*	*Sensitivity Band*
Continuity Index	Greater than or equal 0.80	Minimum service continuity	Report 95% CI
Water Uptime	Greater than or equal 90%	Outage tolerance cap	Season window fixed
Sanitation Functionality	Greater than or equal 85%	Functional service floor	Facility to community

Lifecycle Cost Ratio	Less than or equal 1.10	Budget feasibility bound	Downtime drivers varied
Worst-Slice Continuity	Greater than or equal 0.65	Stress-test safeguard	Across hazard strata

Evaluability Plan: Grouped Bootstrap CI95 and Holdout Flood Seasons

The evaluability plan anchors claims in observable flood-season outcomes and explicitly separates training contexts from held-out seasons. Table (5) specifies grouped and temporal holdouts, a precommitted baseline set, continuity-oriented primary metrics with AC1-AC2 acceptance cues, and leakage guards such as fixed season windows. Baselines emphasize stationarity-based norms and checklist approaches, aligning comparison logic with resilience assessment practice (Ji et al., 2024). Transfer gaps are reported rather than assumed negligible. The acceptance cues also make non-performance explicit.

Uncertainty quantification is operationalized through grouped bootstrap confidence intervals and sensitivity reporting, including a flip-rate check to expose threshold fragility. Fig. (5) outlines how these uncertainty bands and calibration checks are applied under the same grouped split structure. Calibration is treated as a deployment prerequisite: probabilistic thresholds are calibrated on training data, halted when checks fail, and recalibrated for new contexts. These controls address known overconfidence risks in resilience indices (Ji et al., 2024).

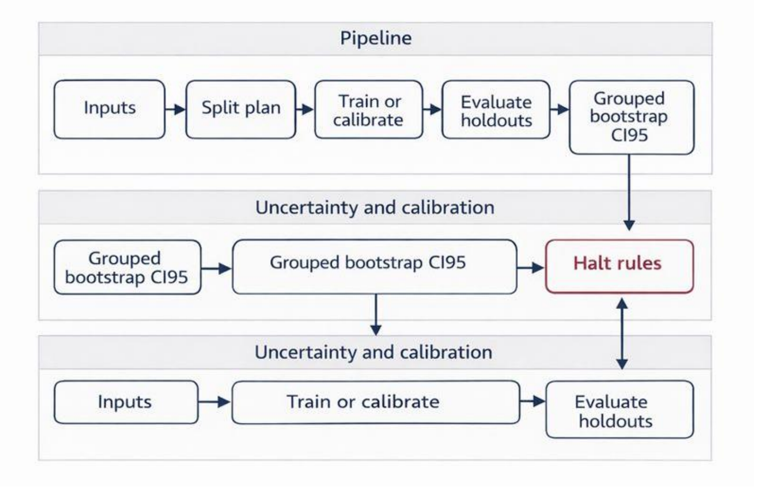

Figure 5. *Validation plan and uncertainty checks*

Table 5. Validation plan overview

Element	*Plan Choice*	*Acceptance Cue*	*Leakage Guard*
Split Scheme	Grouped + temporal holdout	Transfer gap reported	Train-only calibration
Baseline Set	Stationarity + checklists	Beat all baselines	Precommitted list
Primary Metrics	Continuity, uptime, function	AC1-AC2 thresholds	Fixed season window
Secondary Tests	Bootstrap CI + sensitivity	Flip-rate reported	No lookahead
Calibration Check	Probabilistic thresholds	Halt if fails	Recalibrate per context

Illustrative Thought Experiment: High Inundation Duration and Low Maintenance Capacity

The illustrative examples and thought experiments consider a flood-prone rural community facing long inundation duration and low maintenance capacity, a combination that often defeats designs optimized for average conditions. Under this study's decision logic, hazard zoning elevates exposure, while limited O&M capacity constrains feasible response time and repair quality. Complexity becomes a liability. The conservative choice is a low-dependence design package with clear emergency protocols and a halt rule that defaults to safe options when zoning inputs are missing.

Robustness of reasoning is probed by varying two assumptions: access during floods and the reliability of routine maintenance. If access improves or local repair capacity rises, the framework would permit higher-performing but more demanding options, provided continuity and uptime thresholds remain satisfied within the stated acceptance criteria. Alternative explanations for failure are also considered, including supply-chain disruption, power loss, or governance turnover that can mimic hazard effects. Empirical discrimination among these mechanisms is not reported here.

Limitations and Future Work

Indicator-based decision frameworks for flood-resilient rural WASH can fail when proxies shift or inputs are incomplete, a concern also raised for urban resilience indices that weakly align factors to the flood process (Li et al., 2024). Table (6) summarizes limitations, threats to validity, and mitigations, including proxy drift causing mis-zoning and map incompleteness understating hazard. A key limitations boundary is that the present study remains conceptual; empirical validation outcomes are not reported here.

Uncertainty arises from non-transfer thresholds, sparse flood monitoring, and noisy governance measures, so decisions should be accompanied by sensitivity bands, flip-rate reporting, and missingness-aware rules rather than point classifications. Robustness of reasoning therefore requires stress tests across governance and data-quality slices, and conservative penalties when signals are absent. Fig. (6) summarizes failure modes and misuse guardrails that prioritize safe zoning defaults and planned recalibration when transferred to new contexts (Li et al., 2024).

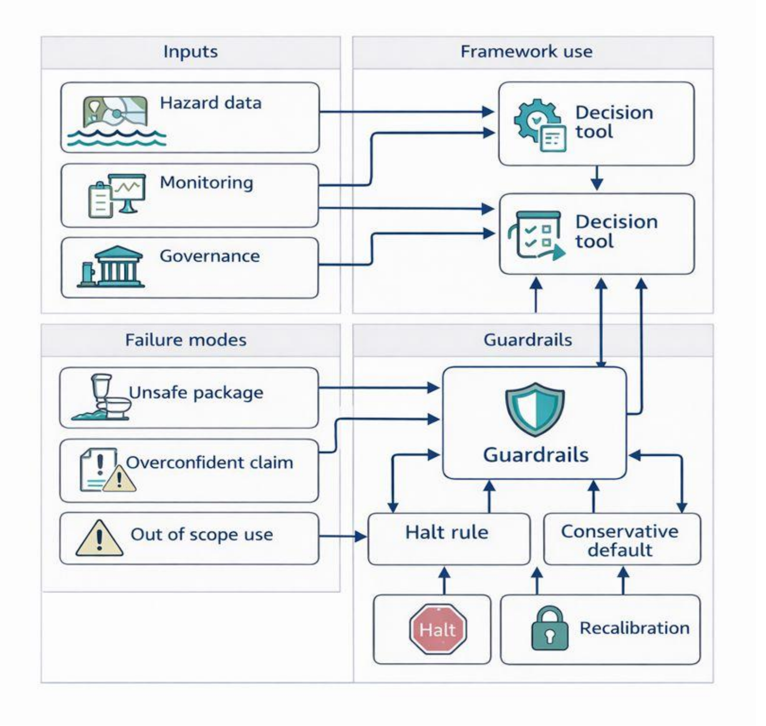

Figure 6. *Failure modes and misuse guardrails*

Table 6. Limitations and mitigations

Limitation	***Threat To Validity***	***Mitigation***	***Robustness Cue***
Proxy drift	Mis-zoning risk	Explicit definitions	Sensitivity bands
Non-transfer thresholds	Decision flip risk	Recalibration plan	Report flip rate
Sparse flood monitoring	Unobserved metrics	Missingness-aware rules	Conservative penalty
Noisy governance measures	False moderation	Triangulate evidence	Slice-based checks
Map incompleteness	Understated hazard	Use model+maps (Flores et al., 2025)	Conservative zoning

Conclusion

The present study frames flood-resilient rural WASH continuity as a linked decision problem spanning hazard zoning, siting, design packages, governance capacity, and operations and maintenance. The theoretical contribution is a mechanism-linked taxonomy that ties structural and governance levers to a flood-season service continuity index. The taxonomy is paired with component metrics for uptime, functionality, contamination incidents, and lifecycle cost ratio. Falsifiable propositions and thresholds anchor subsequent evaluation. The framework is explicitly conceptual; empirical validation is not reported here. Actionability and misuse risk are addressed by encoding feasibility constraints, including a lifecycle cost ratio <= 1.10. Decision rules require continuity >= 0.80 with a 95% confidence interval, together with uptime >= 90% and functionality >= 85%. Worst-slice continuity is constrained to be >= 0.65. Misuse risk increases when zoning inputs are missing or when thresholds are transferred without local calibration. The framework therefore defaults to conservative packages and treats validation as a blueprint, not reported results.

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