

Enhancing Water Security through Hybrid Rainwater Harvesting and Storage Infrastructures

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Abstract: *Rainwater harvesting and storage are widely used in WASH, unfortunately design guidance often treats them as separate parts. This creates an issue in explaining how combined capture and storage options affect water security under different climate, governance, and maintenance capacity conditions. This article provides a practice-oriented conceptual framework that defines water security as availability, reliability, quality protection, access continuity, and maintainability. It then links design logic on redundancy and switching between sources to the pathways that explain how these choices work, with clear boundary conditions. The framework is tested using contrasting illustrative scenarios. It also sets out a path for future evaluation, with candidate metrics, propositions, and implementation questions. The main contribution is a decision logic that can be checked and rebuilt from its steps. It avoids site-specific performance claims and may inform safer real-world use by engineers, NGOs, and policy makers planning rainwater-dependent services.*

Keywords: Hybrid Rainwater Harvesting, Water Security, WASH Practice Settings

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Introduction

This article presents a framework and design logic that link hybrid rainwater harvesting and storage choices to water security within stated climate, governance, and maintenance limits. Water security covers availability, reliability, water quality protection, continuity of access, and maintainability. The contribution is conceptual without new field validation. Claims remain limited to the stated conditions. The approach builds on scenario and scarcity analyses (He et al., 2021; Liu et al., 2022) and on sponge-city synthesis that informs limitations (Kazancı et al., 2025). An illustrative map shows the components in these constraints, Fig. (1).

Study goals and contributions

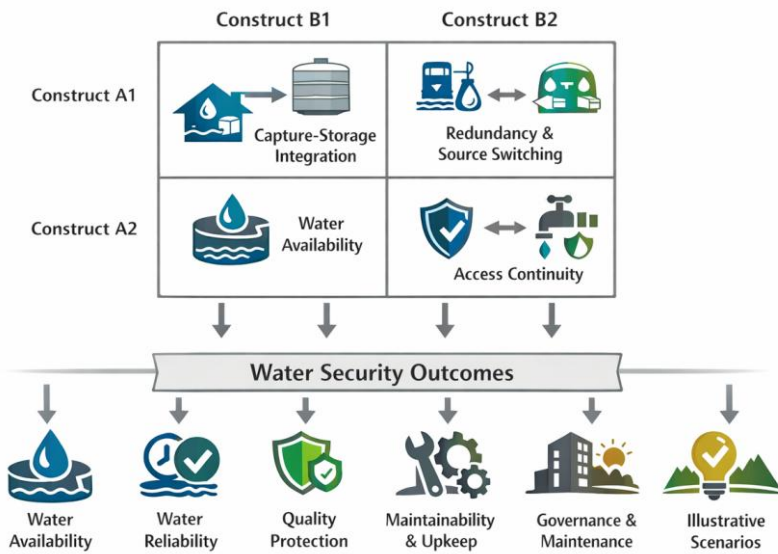


Figure 1. Conceptual framework linking design to constructs

This study presents an integrated framework and practical design logic for hybrid rainwater harvesting and storage to strengthen local water security. The contribution is a framework with clear decision steps for hybrid configurations and not an empirical evaluation. It differs from common guidance by making capture and storage interactions, redundancy, and switching rules explicit, by mapping design elements to a compact set of service constructs, and by providing bounded application rules and non-applicability zones. Fig. (2) illustrates the conceptual framework linking hybrid design choices to the compact water security constructs. Discussion of limitations, regulatory constraints, and

recommended artifact access aligns with reviews of rainwater management and treatment (Raimondi et al., 2023).

Water security constructs

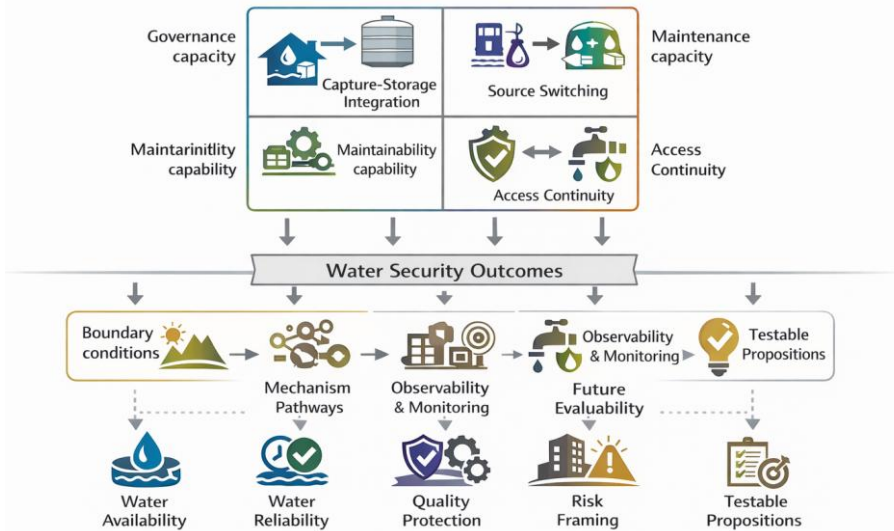


Figure 2. Glossary of water security constructs

The framework defines a compact set of water security constructs that guide later mapping of mechanisms and decision logic. Availability is how often the system provides the intended service and is measured as the fraction of successful service events in Eq. (1). Reliability means consistent delivery over time and under stress. Quality protection covers design and operational steps that prevent contamination and keep water safe to drink. Access continuity describes whether users can reach and use water when needed across place and time. Maintainability captures how practical routine upkeep, repair, and local operation are. Definitions and subgroup distinctions adapt the synthesis in (Mishra et al., 2021). A concise glossary is provided in Fig. (3).

$$Availability = \frac{N_{success}}{N_{total}} \tag{1}$$

Methods

The method uses theory synthesis and analytic design logic to create a hybrid framework that links capture and storage to water security and that can be reconstructed. Source materials were selected using predefined inclusion and exclusion rules and mapped

iteratively to core concepts to preserve precision and traceability (Duan et al., 1992). A process map of the synthesis steps and decision logic is in Fig. (4). A plan for reporting the range of likely values lists bootstrap resampling in Tab. (1). Scenarios were kept separate from evidence claims and guidance was consulted (McFeeters, 1996).

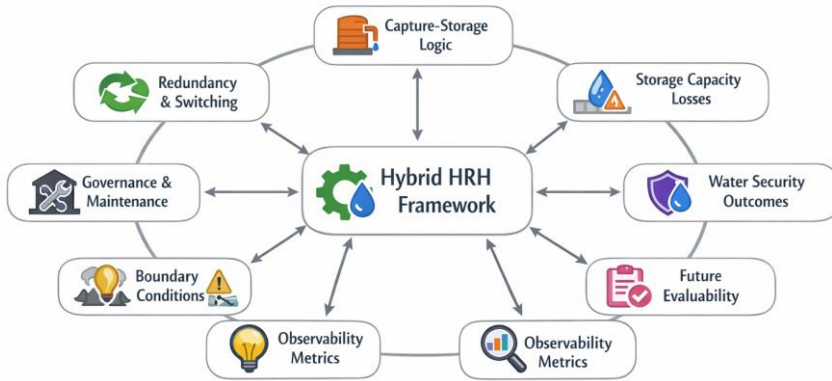


Figure 3. Process map of analytic methods

Table 1. Uncertainty reporting plan.

<i>Aspect</i>	<i>Uncertainty Element</i>	<i>Notes</i>
Bootstrap Approach	Bootstrap resampling (estimates uncertainty)	Illustrative only
Assumptions to Vary	Assumptions to test	Key drivers of uncertainty
Scenarios for Contrast	Scenarios to illustrate	Conceptual only
Boundary Conditions	Non applicability zones	Explicit limits

Source selection and synthesis steps

This section defines rules for selecting and combining adjacent framings for rainwater harvesting, storage, resilience, and water security into a practical framework. Sources were retained only if they explicitly linked a design element, such as capture, storage, redundancy, or switching, to at least one service construct, including availability, reliability, water quality protection, continuous access, or maintainability. Sources lacking descriptions of how a design element would work in practice were excluded. When

guidance conflicted, alternatives were mapped to explicit assumptions and boundary conditions and prioritized by specificity and any stated governance or maintenance preconditions. Provenance and minimal data artifacts, including inventories such as (Zhang & Gu, 2023), were recorded to allow traceability and later reproduction, and rationale for each choice was recorded.

Framework building and checks

The study assembled the schematic, a mechanism map (a causal diagram linking design to service outcomes), and decision logic (rules for selecting configurations). Internal checks covered construct clarity, mechanism traceability, decision transparency, boundary conditions, and evaluability. Theory synthesis using inclusion and exclusion rules produced a compact construct set and definitions. A glossary links constructs to availability, reliability, quality protection, access continuity, and maintainability. Mechanism traceability linked elements to causal pathways, required major elements to have necessary explanatory roles, and annotated moderators: rainfall variability and governance. Decision transparency recorded rules, trade-offs, and assumptions. Boundary conditions listed intended contexts, no applicability zones, and misuse examples. Evaluability specified testable propositions, candidate metrics, and an artifact log.

Results

This study presents analytic outputs from a conceptual synthesis that defines a reconstructable hybrid rainwater harvesting and storage framework to guide practical decision making in water, sanitation and hygiene (WASH) settings. The key outputs are a compact glossary of core concepts, a system diagram that defines the hybrid boundary and switching logic, a mechanism map that links design choices to service concepts, and a short set of testable propositions. All outputs are conceptual artifacts, not measured outcomes, intended to support practitioner reasoning and future empirical testing.

Hybrid system model

The hybrid system model defines the system boundary and the set of components needed to reconstruct an integrated rainwater capture and storage configuration. It explicitly includes capture, conveyance, treatment, storage, distribution, redundancy, and source switching. Capture components include a defined collection area, conveyance, and pre-treatment such as a first flush diversion to protect storage. Storage is a reservoir with a fixed maximum capacity and a discrete mass balance that governs updates. Equation (2) describes the storage update with capacity limits and nonnegativity constraints. Redundancy requires at least one alternative source and overflow pathways that allow interconnection. Source switching is governed by observable triggers, operator rules, or automated control logic. Storage sizing follows benchmark protocol in (Hurst, 1951).

$$S_{t+1} = \max\{0, \min\{S_{max}, S_t + I_t - O_t - L_t\}\} \quad (2)$$

Mechanism pathways and propositions

Pathways link capture, storage, redundancy, and switching to five water security goals: availability (volume), reliability (consistency), quality protection (safe water), access continuity (continuous access), and maintainability (upkeep). The synthesis builds on (Alharbi et al., 2024; Barendrecht et al., 2024). These mechanisms operate as causal links. Capture raises volume. Storage smooths variability and supports reliability. Redundancy and switching avoid single-point failures and sustain access. Protective design limits contamination. Modularity supports upkeep. Pathways are influenced by rainfall variability, storage losses, governance and maintenance, demand, and contamination risk. Three testable propositions follow. Integration raises availability and reliability when governance and maintenance are adequate. Redundancy improves continuity but can increase contamination risk without quality protection. Modular low-complexity designs improve maintainability where operations capacity is low (Boano et al., 2014).

Decision logic and scenario matrix

This section converts rainfall variability, storage losses, demand variability, governance and maintenance capacity into provisional design choices. Illustrative scenarios pressure-test the decision rules. The mapping and benchmarking draw on seasonal scarcity assessment and global water availability projections (Gerten et al., 2011; Mekonnen & Hoekstra, 2016). Operational mappings list operating points: Storage-first for low rainfall, Harvest-first for high rainfall, Hybrid with cushion for moderate demand, and Protection-first with switching when contamination risk is high. Tab. (2). It lists operating points and decision thresholds used to translate context into provisional choices. Illustrative scenarios stress low storage, extreme demand, and governance failure. They reveal trade-offs where capture-storage integration improves availability but may increase water quality risk without protection. These scenarios support evaluation.

Table 2. Operating points and thresholds.

<i>Row Label</i>	<i>Operating Point</i>	<i>Decision Threshold</i>	<i>Notes</i>
Low rainfall	Storage-first	Storage sufficiency	Prioritizes stored water to bridge drought
High rainfall	Harvest-first	Rain capture priority	Direct use favored when rainfall is ample

Moderate demand	Hybrid with cushion	Demand-supply balance	Balances reliability and efficiency
Contamination risk	Protection-first with switching	Quality risk triggers switch	Safeguards water quality and maintainability

Discussion

The discussion explains how the hybrid rainwater harvesting and storage framework, combining capture and storage with extra sources and switching, helps practitioners choose systems under climate, governance, and maintenance limits. Drawing on urban hydrology and policy work, the framework links capture and storage choices to service outcomes (Das & Mishra, 2025; Nlend et al., 2025). It clarifies trade-offs among storage size, maintenance burden, and extra sources, and highlights conflicts between protecting water quality and securing quantity. The text notes that the contribution is conceptual, not evidence of measured effectiveness, and proposes empirical testing.

Positioning against alternatives

The framework is positioned against stand-alone rainwater harvesting, storage-only planning, general water security discourse, and fragmented water, sanitation, and hygiene guidance. It defines water security as availability, reliability, water quality protection, continuity of access, and system maintainability. The framework keeps the focus on capturing and reusing rainwater and revises storage planning to make capture-storage integration, backup options, and source switching explicit, building on decision-support and decentralized systems studies (Garrido-Baserba et al., 2024; Li et al., 2025). Compared with fragmented water, sanitation, and hygiene guidance and broad water security narratives, the framework adds clear decision paths, explicit boundaries, defined failure modes, and concrete action points. It follows global benchmark practice for positioning (Schmitt & Rosa, 2024) and accepts higher local data, governance, and maintenance demands.

Boundary conditions and misuse risks

The framework applies to the design of hybrid rainwater capture and storage systems that combine capture, storage, backup capacity, and explicit switching between sources for seasonal and annual service planning. The approach builds on critiques of assuming past conditions will remain unchanged and on decision tools (Milly et al., 2008; Wang, 2022), and sets operational targets following the service-level objectives in (Milly et al., 2008). The framework is not suitable without redesign or local recalibration where governance or maintenance capacity is very low, where land or space limits prevent enough storage, or

where contamination risk is high and treatment is absent. Concrete failure modes include supply shortfalls when non-stationary rainfall reduces effective yield, overflow and erosion during intense storms, contaminant buildup from inadequate treatment and cleaning, and loss of switching function under weak institutional oversight (Celma et al., 2025).

Future evaluation options

Future studies could evaluate whether the proposed hybrid capture and storage framework improves water security across seasonal and governance conditions. Candidate metrics include service availability measured in days or hours. Reliability can be measured as frequency and duration of outages. Other metrics include indicators of water quality protection, continuity of household or facility access, and maintainability measured by repair time and the fraction of functioning components. Realistic study options include paired before-and-after pilots with matched comparator sites, staggered implementation across rainfall regimes, and comparative multi-site observational cohorts that vary operations and maintenance capacity. Evaluations should use global datasets of starting conditions and infrastructure (Jones et al., 2021; Macedo et al., 2022) and field-scale evapotranspiration data to estimate storage losses and inflow deficits (Melton et al., 2021).

Conclusion

The hybrid framework links rainwater capture, storage, redundancy, and source switching to core water security dimensions. It defines mechanisms and decision rules that show how design choices affect availability, reliability, water quality protection, access continuity, and maintainability. Governance, operations and maintenance capacity, rainfall variability, and contamination risk define explicit limits and cases where the approach does not apply. It supports SDGs 6, 11, and 13 in practice.

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