Household- and Institution-Based Rainwater Harvesting as a Socio-Technical Strategy for Water Security in East Nusa Tenggara

Charisal Akdian Manu[1]*
[1] Civil Engineering Study Program, Akademi Teknik Kupang, Kupang, Indonesia
* Corresponding author: roga.manu@atkup.ac.id

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ABSTRACT

East Nusa Tenggara (Nusa Tenggara Timur, NTT) experiences recurrent seasonal water scarcity driven by a short and spatially variable wet season, prolonged dry periods, limited distributed storage, and uneven access to reliable water services. This study formulates a household- and institution-based rainwater harvesting (RWH) movement as a socio-technical strategy for strengthening local water security. A qualitative applied-conceptual review was conducted using thematic synthesis of peer-reviewed literature, technical guidance, and evidence concerning drought, RWH, water security, community participation, institutional roles, operation and maintenance, and water-quality safeguards. The synthesis identifies households as the distributed foundation of the movement because roof catchments are widely available and water needs are directly experienced, while schools, campuses, government offices, health facilities, and places of worship provide larger catchments and strong demonstration and educational functions. The proposed model integrates five mutually dependent components: education, technical implementation, mentoring, maintenance, and replication. To improve engineering applicability, the model is complemented by screening equations for harvestable volume and storage demand, a risk-based water-quality pathway, stakeholder responsibilities, and measurable implementation indicators. The study concludes that RWH should be promoted not merely as tank installation but as a sustained socio-technical practice linking infrastructure, behavior, institutional ownership, and iterative scaling. Field validation is required to quantify rainfall yield, demand coverage, lifecycle cost, water quality, and performance under local NTT conditions.

Keywords: *East Nusa Tenggara; household water security; institutional rainwater harvesting; rainwater harvesting; socio-technical systems*

ABSTRAK

Nusa Tenggara Timur (NTT) mengalami kelangkaan air musiman yang berulang akibat musim hujan yang singkat dan bervariasi secara spasial, periode kemarau yang panjang, keterbatasan penyimpanan air terdistribusi, serta akses yang belum merata terhadap layanan air yang andal. Penelitian ini merumuskan gerakan pemanenan air hujan (rainwater harvesting/RWH) berbasis rumah tangga dan institusi sebagai strategi sosio-teknis untuk memperkuat ketahanan air lokal. Kajian konseptual-terapan kualitatif dilakukan melalui sintesis tematik terhadap literatur ilmiah, pedoman teknis, dan bukti yang berkaitan dengan kekeringan, RWH, ketahanan air, partisipasi masyarakat, peran institusi, operasi dan pemeliharaan, serta perlindungan kualitas air. Sintesis mengidentifikasi rumah tangga sebagai fondasi terdistribusi karena bidang tangkapan atap tersedia secara luas dan kebutuhan air dirasakan secara langsung, sedangkan sekolah, kampus, kantor pemerintah, fasilitas kesehatan, dan tempat ibadah menyediakan bidang tangkapan yang lebih besar sekaligus fungsi demonstrasi dan edukasi. Model yang diusulkan mengintegrasikan lima komponen yang saling bergantung, yaitu edukasi, implementasi teknis, pendampingan, pemeliharaan, dan replikasi. Untuk meningkatkan keterterapan rekayasa, model dilengkapi persamaan penyaringan untuk volume air yang dapat dipanen dan kebutuhan penyimpanan, jalur perlindungan kualitas air berbasis risiko, pembagian tanggung jawab pemangku kepentingan, serta indikator implementasi yang terukur. Penelitian menyimpulkan bahwa RWH perlu dipromosikan bukan sekadar sebagai pemasangan tangki, melainkan sebagai praktik sosio-teknis berkelanjutan yang menghubungkan infrastruktur, perilaku, kepemilikan institusional, dan replikasi secara bertahap. Validasi lapangan diperlukan untuk mengukur hasil tangkapan hujan, cakupan kebutuhan, biaya siklus hidup, kualitas air, dan kinerja pada kondisi lokal NTT.

Kata Kunci: *Nusa Tenggara Timur; ketahanan air rumah tangga; pemanenan air hujan institusional; pemanenan air hujan; sistem sosio-teknis*

1. INTRODUCTION

Water security in dry and semi-arid regions depends not only on the existence of water resources but also on whether users can obtain adequate quantities of acceptable-quality water when and where it is needed. UN-Water frames water security as sustained access to sufficient and acceptable-quality water for livelihoods, well-being, socio-economic development, protection from water-related risks, and ecosystem preservation. This framing is especially relevant to East Nusa Tenggara (NTT), where water availability is strongly seasonal and the distance between wet-season supply and dry-season demand creates persistent vulnerability.

NTT is repeatedly affected by drought, but the intensity and recurrence of drought vary across the province. Regional frequency analysis by Kuswanto et al. (2021) demonstrates that drought characteristics are spatially heterogeneous, implying that adaptation measures should be tailored to local conditions rather than applied as a single uniform infrastructure response. In practical terms, some communities may require additional household storage, others may benefit from institutional-scale systems, while still others need broader improvements in source protection and supply networks.

Rainwater is therefore an underused local resource. In many settlements, rainfall received by roofs is quickly conveyed to yards and drainage paths, whereas months later the same households and institutions face water deficits. Rainwater harvesting (RWH) addresses this temporal mismatch by intercepting rainfall at the point of occurrence, conveying it through gutters and downpipes, protecting its quality through first-flush and filtration measures, and storing it for designated uses. Modern RWH research emphasizes that the system is not simply a tank; it is an integrated sequence of catchment, conveyance, treatment, storage, demand management, operation, and maintenance (Raimondi et al., 2023).

Indonesian studies also indicate that RWH can increase the accessibility and diversification of water supplies in settlements and institutional environments. Akraboelittaqwa et al. (2021) showed the feasibility of RWH as an alternative clean-water source in an institutional setting when catchment area, rainfall, demand, and water quality are considered. Huwaina et al. (2022) demonstrated its relevance to water-access constraints in settlements, while Ardana et al. (2025) used rainfall-harvesting potential and domestic demand to evaluate drought-mitigation opportunities. These studies support the technical potential of RWH, but implementation sustainability remains contingent on local behavior, maintenance capacity, ownership, affordability, and institutional support.

The implementation problem is therefore socio-technical. A household tank can fail if gutters are not cleaned, first-flush devices are absent, storage is left open, or users do not understand appropriate end uses. Similarly, a school or government-office system can become symbolic infrastructure if no unit is responsible for operation and maintenance. Lumbanbatu (2025) highlights that practical knowledge, local needs, infrastructure conditions, and institutional support influence RWH implementation. This suggests that infrastructure provision alone is insufficient to create durable water-security outcomes.

Households and institutions occupy complementary positions within a scalable movement. Households are the smallest and most widely distributed water-use units; collectively, they offer extensive roof catchment and immediate incentives to reduce dependence on purchased or distant water. Institutions—including schools, universities, government offices, health centres, and places of worship—often possess larger roofs, formal management structures, public visibility, and educational functions. They can therefore operate as demonstration sites, technical learning environments, and replication hubs.

The research gap addressed in this study is the limited integration of these household and institutional roles into a coherent movement model that links physical RWH infrastructure with education, technical mentoring, routine maintenance, governance, and replication. Accordingly, this study asks: (1) What opportunities and constraints shape household- and institution-scale RWH in NTT? (2) How can a simple, participatory, and replicable RWH movement be structured? and (3) What roles should local government, higher education, public institutions, communities, businesses, and households assume to sustain implementation? The objective is to formulate an applied socio-technical framework that can guide pilot projects, local programmes, community service, and subsequent engineering validation.

2. METHODS

2.1 Research Design

This study employed a qualitative applied-conceptual review with a socio-technical analytical orientation. The research did not measure rainfall, household demand, water quality, roof area, or construction cost at a particular site. Instead, it synthesized technical and social evidence to formulate an implementable movement model for household- and institution-based RWH in NTT. The intended output is therefore a conceptual and planning framework rather than a final engineering design.

2.2 Evidence Identification and Selection

The evidence base comprised peer-reviewed journal articles, technical documents, standards, and institutional guidance addressing rainwater harvesting, drought adaptation, water security, household water access, institutional systems, water quality, operation and maintenance, and community participation. Search concepts included “rainwater harvesting,” “household rainwater harvesting,” “institutional rainwater harvesting,” “water security,” “drought adaptation,” “water access,” “East Nusa Tenggara,” and their Indonesian equivalents. Recent publications were prioritized, while older sources were retained when they provided a relevant conceptual or technical foundation.

Sources were retained when they addressed at least one of the following: RWH system components or performance; implementation in households, institutions, public facilities, or water-constrained areas; drought or climate-resilience functions; water-quality or maintenance requirements; social adoption; governance; or replication. Sources discussing water resources only at a broad level without a direct relationship to the research questions were not treated as core evidence.

2.3 Thematic and Socio-Technical Synthesis

Information was extracted into seven analytical themes: (1) drought and water-access vulnerability; (2) household RWH opportunity; (3) institutional RWH opportunity; (4) technical configuration; (5) user behavior and maintenance; (6) institutional and financing support; and (7) replication strategy. The synthesis explicitly treated the technical subsystem—catchment, conveyance, first flush, filtration, storage, overflow, and end use—and the social subsystem—knowledge, affordability, ownership, maintenance routines, institutional responsibility, and community learning—as interdependent.

2.4 Model Formulation and Contextual Assessment

The movement model was formulated by linking recurring requirements across the evidence base into five operational components: education, technical implementation, mentoring, maintenance, and replication. The model was then assessed conceptually against NTT conditions, including seasonal water scarcity, distributed settlements, variable household capacity, institutional roof availability, material accessibility, and the need for low-complexity operation and maintenance. Household, institutional, and regional programme levels were considered to ensure that the framework could be introduced incrementally rather than only through large capital projects.

2.5 Engineering Screening Framework

Although detailed hydrological design was outside the scope of this study, an engineering screening layer was added to prevent indiscriminate tank installation. For a defined period, the potentially harvestable rainwater volume can be estimated as:

$$Vh = P \times A \times C \times \eta$$

where Vh is harvestable volume (m^3), P is rainfall depth (m), A is effective roof catchment area (m^2), C is the runoff coefficient (dimensionless), and η represents system efficiency after first-flush, leakage, and other losses. This relationship is a screening tool only; reliable storage design should use time-series rainfall and demand rather than annual totals alone.

A preliminary storage requirement can be explored through a simple mass-balance concept in which stored volume at time t equals previous storage plus harvested inflow minus demand and controlled losses, subject to the physical tank capacity. This approach makes the key design principle explicit: tank size should be matched to rainfall timing, catchment yield, end-use demand, and desired service reliability. Where overflow is directed to infiltration facilities, Indonesian design should also consider relevant national standards, including SNI 8456:2025 for rainwater infiltration wells and trenches.

2.6 Water-Quality and Safety Considerations

Water quality was treated as a design and management requirement rather than an assumed property of harvested rainwater. The intended end use determines the treatment and monitoring burden. Roof runoff used for cleaning, toilet flushing, or irrigation generally requires lower treatment intensity than water intended for drinking. The WHO sanitary inspection approach for rainwater collection and storage emphasizes risk identification, corrective action, operation, maintenance, and monitoring. Accordingly, the proposed model requires clean catchments, first-flush diversion, protected storage, mosquito-proof openings, periodic cleaning, and treatment appropriate to the intended use.

2.7 Study Limitations

The study is conceptual. It did not conduct site-specific rainfall analysis, roof surveys, daily demand measurements, water-quality testing, construction-cost estimation, or pilot-system monitoring. The proposed equations and implementation indicators therefore serve as screening and planning tools, not as validated performance results. Field studies are required before the framework can support technical specifications or investment decisions for a particular locality.

3. RESULTS

3.1 Household-Level Opportunity and Constraints

Households emerge as the distributed foundation of the proposed movement. Most dwellings possess roof surfaces that can function as catchments, while the benefits of an additional water source are immediately visible to residents. Captured rainwater can support non-potable uses such as toilet flushing, cleaning, laundry pre-wash, yard maintenance, and irrigation, thereby reducing pressure on primary sources. The advantage is cumulative: the contribution of a single roof may be modest, but distributed adoption across many households can create substantial aggregate storage and demand substitution.

The household pathway also has an educational function. Routine actions—cleaning the roof and gutter, operating a first-flush device, keeping the tank covered, inspecting fittings, and reserving water for appropriate uses—translate water conservation from an abstract message into daily practice. This behavioral dimension is essential because technical failure commonly begins with neglected maintenance rather than with the storage tank itself.

Key constraints are initial affordability, limited space, variable roof area, absence of gutters, uncertainty about water quality, and unequal maintenance capacity. A single standardized configuration is therefore inappropriate. The movement should allow graduated entry: simple collection and covered storage where resources are limited, followed by improved filtration, larger storage, demand separation, and overflow management as capacity increases.

3.2 Institutional Opportunity and Demonstration Function

Institutions provide a second and complementary implementation platform. Schools, campuses, government offices, health centres, and places of worship typically have larger roof catchments than individual dwellings and more regular organizational structures. This combination can increase harvestable volume while creating clearer responsibility for inspection, cleaning, repairs, and record keeping.

Institutional systems also produce a public demonstration effect. Schools can integrate the system into environmental and science education; universities can use installations as living laboratories for rainfall measurement, water-quality testing, hydraulic design, and community service; government offices can demonstrate policy consistency; health facilities can model hygienic operation; and places of worship can link stewardship messages with practical water conservation. Thus, the institution is not only a user but also a learning and replication node.

The principal institutional risks are unclear ownership, failure to allocate recurrent maintenance funds, and installation without a defined end-use plan. A technically functional tank is not enough; an institution should designate a responsible unit, document intended water uses, maintain an inspection schedule, and record basic performance information such as rainfall events, storage utilization, maintenance actions, and faults.

3.3 Five-Component Movement Model

The main synthesis result is a five-component movement model: education, technical implementation, mentoring, maintenance, and replication. These components form a sequence but also operate as a feedback system. Education creates informed demand; technical implementation provides visible proof; mentoring reduces design and operational errors; maintenance protects long-term performance; and replication converts isolated projects into a distributed water-security practice.

Table 1. Five-component household- and institution-based RWH movement model

Education	Build water literacy and informed demand	Community sessions; school activities; practical guides; demonstrations; risk communication	Local government; universities; schools; community groups
Technical implementation	Establish a functional and safe RWH system	Roof catchment; gutters; first flush; filtration; covered storage; controlled overflow; designated end use	Households; institutions; technicians
Mentoring	Reduce technical and operational errors	Site screening; simple sizing; installation checks; water-quality advice; user training	Universities; technical agencies; trained community facilitators
Maintenance	Protect performance and water quality	Gutter cleaning; first-flush cleaning; tank inspection; mosquito control; filter replacement; record keeping	Households; institutional facility managers

Replication	Scale successful practice	Demonstration houses; model schools; campus outreach; peer learning; local programmes; CSR support	Government; institutions; communities; businesses

Source: Author's synthesis based on the reviewed literature.

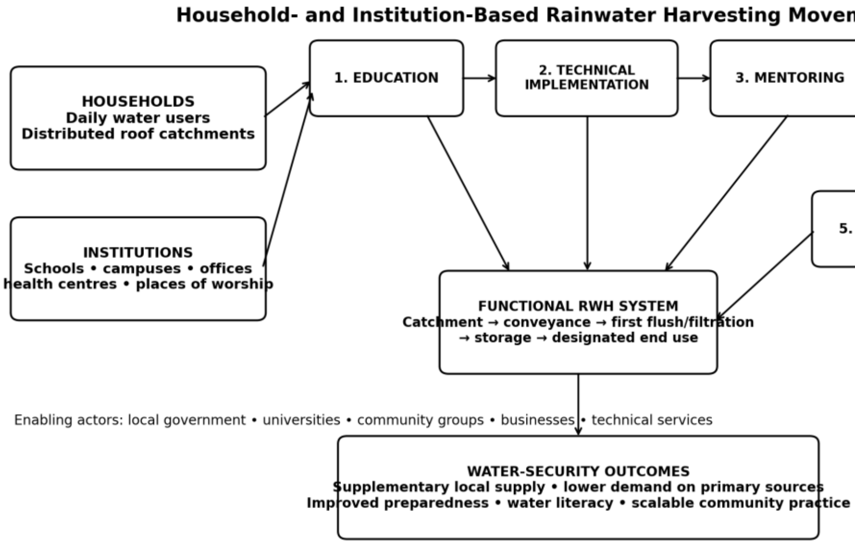

Figure 1. Socio-technical model for a household- and institution-based rainwater harvesting movement.

3.4 Technical Configuration and Screening Design

For both households and institutions, the minimum functional configuration comprises a suitable roof catchment, gutters and downpipes, debris control, first-flush diversion, filtration appropriate to the intended use, protected storage, a controlled outlet, and safe overflow. The configuration should be deliberately linked to demand. For example, a school may prioritize toilets and landscape irrigation, while a household may prioritize cleaning and garden use. Clear separation of potable and non-potable distribution is essential where water is not treated to drinking-water standards.

Screening design should begin with catchment yield rather than with a predetermined tank size. Rainfall depth and temporal distribution, roof area, runoff coefficient, system efficiency, user demand, dry-period duration, available installation space, and budget determine the feasible storage range. For pilots, daily or event-based rainfall records should be paired with measured water demand to construct a simple storage mass balance. This will enable evaluation of supply reliability, overflow frequency, unmet demand, and the marginal benefit of larger tanks.

Table 2. Comparative implementation framework for households and institutions

Catchment	Individual dwelling roof; highly variable area and material	Larger roofs; multiple roof sections may be combined	Measured effective roof area and roof material
Demand priority	Non-potable domestic uses; garden; cleaning	Toilets; cleaning; landscaping; selected operational uses	Daily/weekly end-use demand
Storage	Small-to-medium tank; space and affordability constrained	Larger modular tanks; potential for multiple tanks	Rainfall-demand mass balance and dry-period target
Management	Owner/family responsibility	Designated facility manager or unit	Written maintenance schedule and responsible person
Water-quality control	Simple first flush, screening, protected tank; treatment according to use	Formal inspection and documented maintenance; treatment according to use	Sanitary inspection and periodic testing where appropriate
Replication role	Peer-to-peer neighborhood example	Demonstration, education, training, and institutional outreach	User feedback, performance records, and documented lessons

Source: Author's synthesis and proposed implementation framework.

3.5 Water-Quality Protection and Operation & Maintenance

Water-quality protection is a non-negotiable component of the movement. The 2026 WHO sanitary inspection package for rainwater collection and storage reinforces a risk-management approach that combines infrastructure inspection with ongoing operation, maintenance, monitoring, and corrective action. For the proposed NTT movement, a basic safety chain includes periodic roof and gutter cleaning, exclusion of animal access, first-flush diversion after dry periods, covered storage, protected inlets and outlets, mosquito control, sediment removal, and treatment appropriate to the intended use.

The movement should avoid a common communication error: describing all harvested rainwater as "clean water" without qualification. Water suitable for toilet flushing or irrigation is not automatically suitable for drinking. Any potable use requires site-specific treatment and verification against applicable drinking-water requirements. Clear labeling of non-potable outlets is also advisable for institutional systems.

3.6 Governance, Financing, and Actor Responsibilities

Local government has the strongest role in creating enabling conditions through guidance, demonstration programmes, small-scale subsidies or material support for vulnerable households, integration with drought adaptation and disaster-risk reduction, and requirements or incentives for public facilities. Higher education institutions can provide rainfall analysis, simple design tools, water-quality testing, training, and monitoring protocols. Communities contribute local ownership and peer replication, while businesses can support tanks, guttering, filters, monitoring equipment, and training through corporate social responsibility or partnership mechanisms.

The recommended financing principle is incremental rather than infrastructure-maximalist. Pilot programmes can begin with a small number of representative households and institutions, monitor technical and social performance for at least one wet-to-dry seasonal transition, and then scale configurations that demonstrate acceptable reliability, maintenance burden, and user acceptance. This reduces the risk of distributing equipment that is poorly matched to local rainfall, demand, or maintenance capacity.

3.7 Monitoring Indicators and Replication Pathway

Replication should be evidence-led. A movement becomes credible when installations are not only visible but demonstrably used, maintained, and beneficial. Accordingly, technical, behavioral, institutional, and water-security indicators should be monitored together.

Table 3. Suggested indicators for pilot monitoring and replication decisions

Technical performance	Harvested volume; tank overflow frequency; days of usable storage; downtime; leakage	Determines whether the design matches rainfall and demand
Water quality and safety	Sanitary inspection score; tank closure; first-flush function; selected water-quality tests	Protects users and identifies corrective actions
Use and demand substitution	Volume used by end use; reduction in primary-source use; frequency of tank use	Tests whether stored water provides a practical service
Operation and maintenance	Cleaning frequency; filter replacement; repair response time; responsible person identified	Measures long-term functionality
Affordability	Capital cost; annual maintenance cost; cost per unit of water supplied where measurable	Supports scale-up and subsidy design
Behavior and learning	User knowledge; student/community participation; peer adoption	Captures the movement's social mechanism
Replication	Number of functioning follow-on installations; institutions adopting the model; local budget/programme support	Shows transition from pilot project to sustained practice

Source: Proposed indicators for future field validation.

4. DISCUSSION

4.1 Contribution to Water Security in NTT

The proposed framework strengthens the original RWH concept by explicitly connecting water infrastructure with the broader dimensions of water security. RWH cannot eliminate NTT's structural water challenges, nor should it be presented as a replacement for reservoirs, raw-water systems, piped supply, groundwater protection, or other large-scale infrastructure. Its value lies in diversification: it creates a supplementary water source close to users, increases preparedness for short interruptions and early dry-season stress, and can reduce demand on more constrained sources for selected non-potable uses.

This diversification function is consistent with the broader water-security perspective that resilience depends on adequate access, acceptable quality, risk reduction, affordability, and institutional capacity rather than on a single source. At household scale, the benefit is proximity and control over a small local reserve. At institutional scale, the benefit combines operational water substitution with demonstration and education. These complementary functions justify treating households and institutions as two interconnected implementation platforms rather than separate target groups.

4.2 Socio-Technical Novelty of the Movement Model

The conceptual contribution of this study is the five-component progression from education to replication. Conventional project logic often begins with procurement and installation; the proposed movement begins with user understanding and ends with evidence-based scale-up. This sequence changes the success criterion from "number of tanks installed" to "number of systems functioning, safely used, maintained, and replicated." The shift is important for civil-engineering interventions whose performance depends on user behavior after construction.

The model also clarifies why institutional demonstration sites can accelerate household uptake. A well-operated school, campus, office, health centre, or place of worship can reduce uncertainty about system design, provide a visible reference for maintenance, and create a local training site. Universities are particularly valuable because they can connect engineering calculations with field measurements and community education. In this sense, institutional systems can function as living laboratories and knowledge infrastructure.

4.3 Engineering and Policy Implications

For engineering practice, the principal implication is that RWH should be designed from quantified catchment yield and end-use demand, even when the final installation is simple. Tank procurement without rainfall-demand analysis can create two opposite failures: undersized systems that overflow frequently and provide little dry-season benefit, or oversized systems that consume scarce funds without corresponding gains in service reliability. Simple mass-balance analysis and pilot monitoring can substantially improve design decisions.

For policy, the most appropriate near-term pathway is a tiered programme: demonstration and monitoring at selected public institutions; support for representative households with different roof, income, and space conditions; development of illustrated local technical guidance; training of community and institutional operators; and incorporation of proven configurations into district or provincial drought-adaptation, sanitation, school-infrastructure, and climate-resilience programmes. Where overflow is intentionally infiltrated, the design should be integrated with site suitability and relevant Indonesian standards rather than treated as an informal disposal route.

4.4 Water Safety as a Condition for Scaling

Scaling without water-safety safeguards could undermine public confidence and create preventable health risks. The WHO risk-based sanitary inspection framework is therefore highly relevant to the proposed movement. Even when harvested rainwater is intended only for non-potable uses, protected storage, clean conveyance, exclusion of animals and mosquitoes, maintenance records, and corrective-action procedures are appropriate minimum controls. Potable use requires a substantially stronger treatment and verification pathway and should not be assumed from visual clarity alone.

4.5 Limitations and Research Agenda

The main limitation is the absence of empirical validation. The framework was derived through literature and conceptual synthesis and therefore does not demonstrate actual water savings, cost effectiveness, water quality, or user adoption in NTT. The next research phase should establish pilot sites across contrasting settings and collect at least one complete wet-to-dry seasonal cycle of rainfall, roof runoff, tank levels, water use, overflow, water quality, maintenance actions, user acceptance, and costs. These data would enable calculation of demand coverage, reliability, storage efficiency, cost per cubic metre supplied, and maintenance burden.

Future research should also compare household and institutional performance, test alternative tank sizes and first-flush configurations, investigate roof-material effects on water quality, evaluate willingness to pay and subsidy options, and examine whether institutional demonstration accelerates neighborhood adoption. Such work would transform the present conceptual movement into an evidence-based regional implementation protocol.

5. CONCLUSION

Household- and institution-based rainwater harvesting has strong potential as a complementary water-security strategy for East Nusa Tenggara because it converts locally available wet-season rainfall into a distributed reserve close to users. Households provide the broad adoption base and immediate demand incentive, while institutions contribute larger catchments, formal management, public visibility, and educational functions.

The proposed movement consists of five interdependent components: education, technical implementation, mentoring, maintenance, and replication. Its central proposition is that RWH should not be evaluated by physical installation alone. Sustainable performance requires appropriate sizing, safe conveyance and storage, defined end uses, water-quality protection, routine maintenance, accountable management, and evidence-led scaling. The framework is deliberately compatible with incremental implementation, from simple household systems to institutional demonstration sites and local government programmes.

Because this study is conceptual, field validation remains essential. Pilot projects should quantify rainfall yield, storage reliability, demand substitution, lifecycle cost, water quality, maintenance performance, and user acceptance under different NTT conditions. These results can then support local design guidance and more defensible decisions on wider replication.

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AUTHOR CONTRIBUTIONS

The author was solely responsible for conceptualization, research design, literature identification and synthesis, development of the socio-technical rainwater harvesting framework, formulation of the engineering screening and monitoring components, interpretation of the findings, visualization, manuscript preparation, critical revision, and approval of the final version for publication.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest related to the publication of this article.

DATA AVAILABILITY STATEMENT

No primary dataset was generated in this conceptual study. The evidence supporting the synthesis is available in the cited publications and technical sources.

ETHICAL STATEMENT

This study was conducted in accordance with academic research ethics. It did not involve human participants, personal data, animals, or experimental interventions. All external sources have been acknowledged.

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