An Integrative Rainwater Harvesting–Artificial Recharge Model for Drought Adaptation in East Nusa Tenggara

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ABSTRACT

East Nusa Tenggara (Nusa Tenggara Timur, NTT) is recurrently exposed to drought because rainfall is strongly seasonal, the dry season is prolonged, storage is limited in many settlements, and a substantial share of wet-season runoff is not retained for later use. This study formulates an integrative rainwater harvesting (RWH)–artificial recharge model as a context-sensitive drought adaptation strategy for NTT. A qualitative applied-conceptual review was undertaken through thematic synthesis of peer-reviewed studies, technical standards, institutional reports, and established guidance on drought, RWH, groundwater conservation, infiltration structures, and managed aquifer recharge (MAR). The synthesis distinguishes two complementary functions: RWH provides a decentralized short-term water buffer, whereas artificial recharge converts controlled overflow into medium- to long-term subsurface storage. The resulting model comprises five linked stages—capture, store, use, recharge, and govern—and is organized across household, institutional, and area-wide implementation scales. To improve engineering applicability, the model is supplemented with a screening framework covering rainfall and demand, runoff coefficient, infiltration capacity, groundwater depth, vadose-zone thickness, source-water quality, contamination risk, and operation-and-maintenance capacity. The study argues that integration is preferable to stand-alone storage or recharge because it couples immediate demand reduction with groundwater conservation and runoff attenuation. However, implementation requires site-specific hydrologic and hydrogeologic assessment, water-quality safeguards, and monitoring before structural design. The model provides a practical conceptual basis for pilot projects, feasibility studies, and drought-resilience planning in semi-arid island settings such as NTT.

Keywords: *artificial recharge; drought adaptation; East Nusa Tenggara; managed aquifer recharge; rainwater harvesting*

ABSTRAK

Nusa Tenggara Timur (NTT) berulang kali mengalami kekeringan karena curah hujan sangat bersifat musiman, musim kemarau berlangsung panjang, kapasitas penyimpanan air terbatas di banyak permukiman, dan sebagian besar limpasan musim hujan belum ditahan untuk penggunaan pada periode berikutnya. Penelitian ini merumuskan model integratif pemanenan air hujan (rainwater harvesting/RWH)–recharge buatan sebagai strategi adaptasi kekeringan yang peka terhadap konteks NTT. Kajian konseptual-terapan kualitatif dilakukan melalui sintesis tematik terhadap artikel ilmiah, standar teknis, laporan institusi, dan pedoman yang mapan mengenai kekeringan, RWH, konservasi air tanah, struktur infiltrasi, serta managed aquifer recharge (MAR). Sintesis membedakan dua fungsi yang saling melengkapi: RWH menyediakan penyangga air terdesentralisasi untuk jangka pendek, sedangkan recharge buatan mengubah limpasan berlebih yang terkendali menjadi penyimpanan bawah permukaan untuk jangka menengah hingga panjang. Model yang dihasilkan terdiri atas lima tahap yang saling terhubung—capture, store, use, recharge, dan govern—serta diterapkan pada skala rumah tangga, institusi, dan kawasan. Untuk meningkatkan keterterapan rekayasa, model dilengkapi kerangka penyaringan yang mencakup curah hujan dan kebutuhan air, koefisien limpasan, kapasitas infiltrasi, kedalaman air tanah, ketebalan zona tak jenuh, kualitas air sumber, risiko kontaminasi, serta kapasitas operasi dan pemeliharaan. Integrasi dinilai lebih tepat daripada penyimpanan atau recharge yang berdiri sendiri karena menggabungkan pengurangan kebutuhan air secara langsung dengan konservasi air tanah dan pengendalian limpasan. Namun, penerapannya tetap memerlukan kajian hidrologi dan hidrogeologi spesifik lokasi, pengamanan kualitas air, dan pemantauan sebelum desain struktur dilakukan.

Kata Kunci: *adaptasi kekeringan; pemanenan air hujan; recharge buatan; managed aquifer recharge; Nusa Tenggara Timur*

1. INTRODUCTION

Water security in semi-arid regions is determined not only by annual rainfall volume but also by the timing, concentration, storage, and spatial distribution of water. In East Nusa Tenggara (NTT), domestic supply, sanitation, agriculture, livestock, public health, and local economic activities are repeatedly affected by a pronounced seasonal imbalance: rainfall is concentrated within a relatively short wet season, whereas water demand persists throughout a much longer dry period. Under these conditions, drought is best understood as a mismatch between when water becomes available and when it is needed, compounded by limited storage and uneven access to reliable water infrastructure.

Empirical studies confirm that drought in NTT is recurrent and spatially heterogeneous. Kuswanto et al. (2021), using regional frequency analysis of rainfall records, demonstrated that extreme drought can recur within relatively short return periods in parts of the province. More recent remote-sensing analysis by Kusmiyarti et al. (2024) found that drought severity in NTT is influenced by seasonal dynamics, climate variability, land-cover conditions, seasonal farming, and land fires. These findings are important for engineering planning because they indicate that a uniform province-wide intervention is unlikely to perform equally well across islands, districts, watersheds, and settlements.

Climate change adds further uncertainty to this seasonal water imbalance. The IPCC identifies drought, groundwater depletion, and extreme rainfall as water-related hazards that are already prompting adaptation responses such as rainwater harvesting, soil-moisture conservation, and other forms of decentralized water management (IPCC, 2022). For NTT, this means that drought adaptation should not rely solely on expanding conventional water-supply infrastructure. It should also increase the ability of buildings, institutions, settlements, and catchments to retain rainfall during wet periods and preserve part of that water for use during dry periods.

Rainwater harvesting (RWH) offers a direct way to achieve this objective. At building scale, rainfall can be intercepted from roofs and other suitable catchments, conveyed through gutters and downpipes, filtered or diverted through first-flush devices, and stored in tanks or reservoirs. RWH can therefore reduce demand on piped water, wells, tankered supply, and other external sources. Reviews by Raimondi et al. (2023) and Judeh et al. (2022) show that RWH can contribute simultaneously to water-supply reliability and stormwater management, particularly when storage, water-quality control, and system operation are explicitly considered. Indonesian experience also demonstrates its relevance in water-limited settings; for example, Ardana et al. (2025) reported that harvested rainfall in a drought-prone village in Bali could exceed estimated annual domestic demand under the assessed conditions.

Nevertheless, storage alone has a structural limitation: tank capacity is finite. During intense wet-season events, a tank can fill rapidly, after which overflow again becomes surface runoff. Conversely, during a prolonged dry season, even a large tank may eventually be depleted. These limitations suggest that RWH should be designed as the first component of a broader water-conservation system rather than as an isolated intervention.

Artificial recharge, increasingly framed internationally as managed aquifer recharge (MAR), provides the complementary function. MAR intentionally enhances groundwater recharge using structures such as recharge wells, infiltration trenches, spreading basins, infiltration ponds, recharge dams, or aquifer storage and recovery systems where hydrogeologic conditions allow. UNESCO case studies demonstrate that MAR can increase groundwater storage, buffer drought, support environmental flows, and in some settings improve water quality through subsurface treatment processes (Zheng et al., 2021). Recent reviews further emphasize that the effectiveness of MAR depends on hydrogeology, source-water quality, recharge method, monitoring, and governance (Sufyan et al., 2024; Gebreslassie et al., 2025).

The technical rationale for integrating RWH with artificial recharge is therefore straightforward. Rainfall is first captured and allocated to beneficial direct use; only surplus or controlled overflow is routed to infiltration or recharge structures. Such a cascade can reduce immediate demand, attenuate runoff, and enhance groundwater storage within one coordinated system. Abd-Elaty et al. (2024) demonstrated the potential of combined RWH–MAR in an arid-region application, where the integrated approach increased modeled aquifer storage and reduced the loss of runoff to the sea. Although those quantitative results cannot be transferred directly to NTT, the system logic is highly relevant to an island province where seasonal rainfall and dry-season water scarcity coexist.

The research gap addressed by this study is not the absence of individual RWH or recharge technologies, but the lack of a simple integrative framework that connects short-term water storage, controlled use, groundwater recharge, technical screening, and institutional governance for the specific drought-adaptation context of NTT. Accordingly, the study addresses three questions: (1) What characteristics of drought and rainwater utilization in NTT justify an integrated intervention? (2) How can RWH and artificial recharge be combined into an adaptive water-management model? and (3) What technical, social, and institutional conditions are required for sustainable implementation? The objective is to formulate an applied conceptual model that can guide pilot projects, feasibility studies, public-facility retrofits, community programs, and subsequent site-specific engineering design. The principal novelty is a five-stage capture–store–use–recharge–govern framework linked to three implementation scales and to explicit technical screening and monitoring criteria.

2. METHODS

2.1 Research Design

This study employed a qualitative applied-conceptual review design. The purpose was not to estimate causal effects statistically or to produce a site-specific hydraulic design, but to synthesize available scientific and technical evidence into an implementable conceptual model for drought adaptation in East Nusa Tenggara. The design is therefore exploratory in knowledge synthesis and applied in its intended use. The unit of analysis is the relationship among seasonal drought, decentralized rainwater harvesting, controlled overflow, artificial or managed aquifer recharge, and the governance conditions required to keep these systems functional over time.

2.2 Scope of Evidence and Source Selection

The evidence base included peer-reviewed journal articles, academic books and reviews, institutional publications, and technical standards related to drought, rainwater harvesting, groundwater recharge, infiltration facilities, water quality, semi-arid water management, and climate adaptation. Literature published within the most recent five years was prioritized where available, while older sources were retained when they provided foundational concepts or established technical guidance. Sources were considered relevant when they addressed at least one of the following domains: (a) drought characteristics in NTT or comparable semi-arid settings; (b) RWH design, performance, or water quality; (c) artificial recharge or MAR methods; (d) hydrologic or hydrogeologic suitability factors; or (e) institutional arrangements for long-term water-system operation.

For the NTT context, the synthesis gives particular weight to studies that directly assess drought within the province, including regional frequency analysis (Kuswanto et al., 2021) and remote-sensing drought monitoring (Kusmiyarti et al., 2024). For the technology component, the synthesis draws on recent RWH reviews and applications (Judeh et al., 2022; Raimondi et al., 2023; Ardana et al., 2025), MAR guidance and reviews (Zheng et al., 2021; Sufyan et al., 2024; Gebreslassie et al., 2025), and an integrated RWH–MAR application in an arid setting (Abd-Elaty et al., 2024). Technical conformity for Indonesian infiltration wells and trenches should be checked against the current national standard, SNI 8456:2025, at the detailed design stage (Badan Standardisasi Nasional, 2025).

2.3 Information Extraction and Thematic Synthesis

Information was extracted conceptually into six themes: drought drivers and impacts; rainwater availability and catchment potential; storage and direct-use functions; recharge technologies and hydrogeologic controls; water-quality and contamination risks; and governance, maintenance, and institutional responsibilities. The analysis then linked these themes through a functional question: what should happen to rainfall from the moment it reaches a catchment until it is either used, safely returned to the subsurface, or discharged? This question provided the organizing logic for the five-stage model.

2.4 Model Formulation

The model was formulated using a cascade principle. Direct beneficial use is prioritized before recharge because household and institutional RWH can immediately reduce demand on scarce conventional supplies. Once short-term storage or operational demand is satisfied, controlled overflow is routed to an appropriate recharge structure. The final stage, governance, is treated as part of the engineering system rather than as an external administrative activity because maintenance, sediment removal, tank hygiene, source-water protection, and monitoring determine whether the hydraulic assets continue to perform as intended.

2.5 Screening-Level Engineering Relationships

Although the study does not undertake site-specific sizing, the conceptual model can be operationalized through screening-level water-balance relationships. The gross harvestable rainwater volume from a catchment can be approximated as:

$$Vh = P \times A \times C \times \eta \qquad (1)$$

where Vh is harvestable rainwater volume, P is rainfall depth over the selected time step, A is catchment area, C is the runoff coefficient, and η represents collection efficiency after first-flush diversion, conveyance losses, and other system losses. For detailed design, each parameter should be derived from local rainfall records, catchment material, roof geometry, and operational conditions rather than transferred from generic assumptions.

A conceptual expression for the volume available for managed recharge is:

$$Vr = \max [0, Vh - Ud - \Delta S - L] \quad (2)$$

where Vr is controlled recharge volume, Ud is direct beneficial use during the time step, ΔS is the change in storage retained in tanks or ponds, and L represents losses such as evaporation, leakage, sedimentation-related unusable volume, or intentional bypass. Equation (2) is not a design formula for a recharge well; it is a water-allocation logic showing that recharge should be based on verified surplus after safe use and storage requirements are considered. Recharge capacity must subsequently be checked against infiltration rate, soil and rock properties, groundwater depth, aquifer characteristics, and water-quality constraints.

2.6 Contextual Suitability Assessment

Suitability for NTT was assessed conceptually across four dimensions. The hydrologic dimension considers rainfall seasonality, runoff generation, storage need, and the timing of demand. The technical dimension considers catchment condition, tank sizing, infiltration capacity, groundwater depth, topography, and the suitability of recharge structures. The social-economic dimension considers affordability, user practices, maintenance capacity, and the value of reducing dependence on purchased or transported water. The institutional dimension considers the roles of local government, universities, communities, facility managers, private-sector partners, and water-service institutions. These dimensions are used to prevent the model from being interpreted as a one-size-fits-all construction detail.

2.7 Standards and Technical References

Detailed infiltration-well and infiltration-trench design in Indonesia should comply with applicable national standards and local regulations. The current BSN catalogue lists SNI 8456:2025, “Sumur dan parit resapan air hujan” (rainwater infiltration wells and trenches), as an applicable national standard. The conceptual model in this paper does not substitute for that standard. Instead, it defines where such structures fit in an integrated water-management chain and identifies the information that should be collected before detailed engineering design.

2.8 Study Limitations

This research does not include direct measurements of rainfall, runoff discharge, infiltration rate, hydraulic conductivity, groundwater levels, aquifer thickness, water quality, or household water demand at a specific pilot site. It also does not conduct hydrologic simulation, groundwater modeling, life-cycle costing, or structural design. Consequently, the proposed model should be interpreted as a planning and research framework. Any implementation must be preceded by local field investigation and, for larger MAR systems, hydrogeologic assessment, recharge testing, water-quality evaluation, permitting, and monitoring design.

3. RESULTS

3.1 Drought and Rainwater-Management Context in East Nusa Tenggara

The synthesis indicates that the core water-management problem in NTT is temporal asymmetry. Rainfall occurs during a limited wet-season window, while domestic, agricultural, livestock, sanitation, and institutional water demands continue across the year. When rainfall is intense, water can leave roofs, roads, and hillslopes rapidly as runoff; when the dry season is prolonged, local surface sources and shallow groundwater become increasingly stressed. This means that drought adaptation requires both retention and redistribution of wet-season water over time.

The regional evidence also indicates substantial spatial heterogeneity. Kuswanto et al. (2021) showed that drought behavior differs across rainfall stations and that extreme events may recur frequently in parts of NTT. Kusmiyarti et al. (2024) further demonstrated spatial and temporal variability in drought exposure from 2018–2023 and linked severe conditions to climate variability, seasonal farming, vegetation dynamics, and land fires. The practical implication is that the same RWH tank size, recharge-well design, or conservation-pond configuration should not be replicated mechanically across the province. A common framework is useful, but physical dimensions must remain site-specific.

This synthesis therefore reframes rainwater as a strategic seasonal resource. The adaptation opportunity is not simply to “find more water” during drought, but to reduce the fraction of wet-season rainfall that is lost without beneficial use. The model consequently prioritizes three destinations for rainfall: direct use, temporary surface storage, and controlled subsurface storage.

3.2 Rainwater Harvesting as the First-Line Intervention

RWH is identified as the first-line intervention because it can be deployed incrementally and close to the point of demand. At household scale, a basic system consists of a roof catchment, gutter, downpipe, first-flush device or initial diversion, filter, storage tank, outlet, and overflow line. At institutional scale, larger roof areas can support higher capture volumes and can also serve as demonstration sites for schools, campuses, government offices, health facilities, and places of worship.

The principal benefit is demand substitution. Harvested water can be assigned first to non-potable uses such as cleaning, toilet flushing, landscape irrigation, and other uses compatible with the achieved water quality. Potable use requires an appropriate treatment barrier and verified compliance with drinking-water requirements; captured rainwater should never be assumed potable merely because it originates from rainfall. Raimondi et al. (2023) and Judeh et al. (2022) emphasize that roof material, atmospheric deposition, first-flush quality, storage conditions, and microbial contamination can materially affect harvested-water quality.

RWH also reduces storm runoff while storage is available. However, the magnitude of this benefit depends on tank capacity, antecedent storage, rainfall pattern, and operational drawdown. Therefore, the model treats overflow not as system failure but as a managed resource that should be directed, where suitable, toward recharge rather than discharged immediately.

3.3 Artificial Recharge as the Long-Term Conservation Component

Artificial recharge extends the temporal value of harvested rainfall by moving controlled surplus into subsurface storage. The most appropriate technology depends on hydrogeologic conditions. Shallow infiltration wells and trenches can be suitable where near-surface materials have adequate infiltration capacity and sufficient vertical separation from groundwater. Infiltration ponds or conservation ponds may be suitable where land is available and surface spreading is feasible. Deeper recharge wells or aquifer storage and recovery require substantially stronger hydrogeologic characterization, water-quality control, monitoring, and operational expertise.

The synthesis identifies four non-negotiable prerequisites for recharge: adequate infiltration or hydraulic connection to the target aquifer, acceptable source-water quality, protection from contaminant pathways, and a maintenance plan. These requirements are consistent with recent MAR reviews, which stress that recharge projects must consider both water quantity and quality rather than maximizing infiltration alone (Sufyan et al., 2024; Gebreslassie et al., 2025).

For NTT, this distinction is especially important because local geology and topography vary considerably across islands and settlements. Areas with thin soils, steep slopes, low-permeability formations, shallow contaminated groundwater, or sensitive karst systems may require different solutions or may be unsuitable for conventional infiltration wells. Thus, the model prescribes technical screening before structure selection.

3.4 The Five-Stage Integrative Model

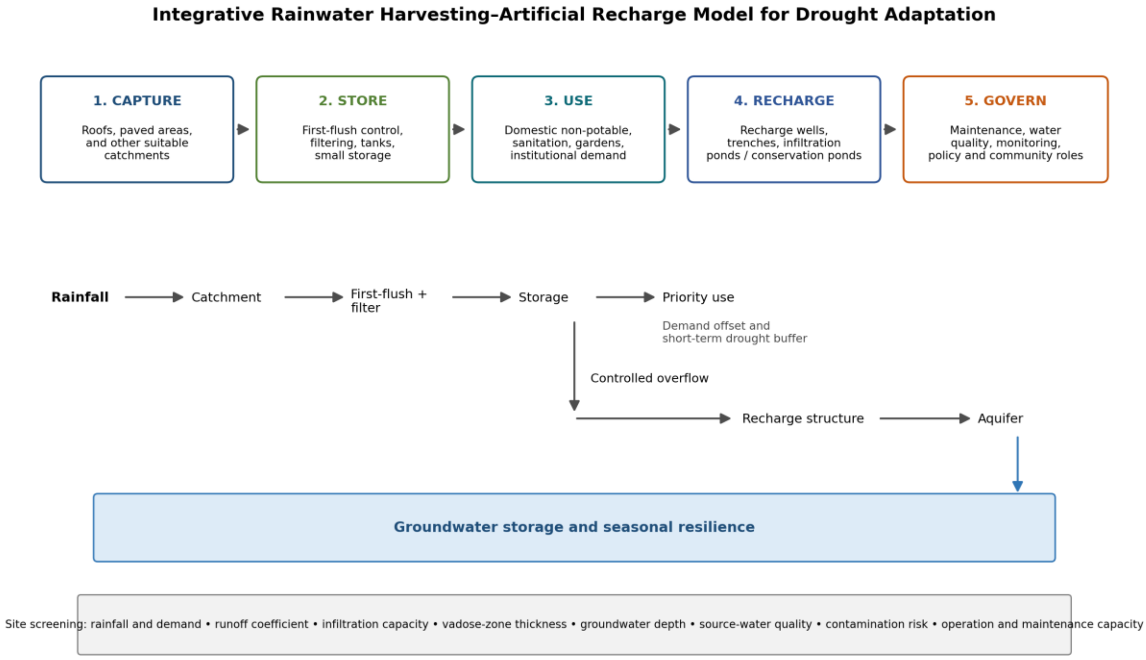
The principal result of the study is the integrative capture–store–use–recharge–govern model shown in Figure 1. The stages are sequential in hydraulic logic but iterative in operation. Rainfall is captured from suitable surfaces; stored after first-flush control and filtering; allocated to beneficial use; excess water is routed to an appropriate recharge structure; and the entire system is governed through maintenance, water-quality management, monitoring, financing, and institutional responsibilities. The model therefore links short-term drought buffering with longer-term groundwater conservation rather than treating them as separate programs.

Table 1. Components of the Integrative Rainwater Harvesting–Artificial Recharge Model

1	Capture rainfall	Intercept water before it becomes uncontrolled runoff	Roofs, institutional buildings, selected paved catchments, other clean catchments
2	Store and pre-treat	Create short-term reserve and protect storage quality	First-flush devices, screens, filters, tanks, small reservoirs
3	Use	Offset demand for suitable end uses	Sanitation, cleaning, landscape irrigation, selected domestic/institutional uses
4	Recharge surplus	Reduce runoff and support subsurface storage	Infiltration wells, trenches, infiltration ponds, conservation ponds; advanced MAR where justified
5	Govern and monitor	Sustain hydraulic and water-quality performance	Maintenance, sediment control, water-quality checks, groundwater monitoring, financing, policy, community management

Source: Author's conceptual synthesis based on the reviewed literature and technical guidance.

Figure 1. Integrative Rainwater Harvesting–Artificial Recharge Model for Drought Adaptation.



Source: Author's conceptual synthesis. The figure represents a planning framework; site-specific design requires local hydrologic, hydrogeologic, water-quality, and regulatory assessment.

3.5 Implementation Scales and Technical Decision Logic

The model is designed for three nested implementation scales. Household systems emphasize affordability, direct water savings, and simple infiltration structures where suitable. Institutional systems use larger catchment areas and can incorporate better monitoring, treatment, educational functions, and standardized maintenance. Area-wide systems aggregate runoff and require formal engineering assessment for conservation ponds, infiltration networks, recharge dams, or advanced MAR. The three scales are complementary: distributed household and institutional capture can reduce local demand and runoff, while strategically located area-wide recharge can address catchment-scale water conservation.

Table 2. Scale-Specific Implementation Framework

Household	Roof catchment, first flush, filter, tank	Simple infiltration well/trench where compliant and suitable	Roof area; rainfall; demand; tank hygiene; infiltration; groundwater	Short-term water reserve and reduced external water demand

			depth; setback from contamination sources	
Institutional	Large roof catchment, modular tanks, metering, controlled distribution	Multiple infiltration wells/trenches or infiltration garden/pond	Catchment quality; storage reliability; end-use separation; infiltration testing; maintenance responsibility	Higher capture volume, public demonstration, education, runoff reduction
Area-wide	Distributed capture plus drainage/retention network	Conservation pond, infiltration basin, recharge dam, or engineered MAR	Watershed runoff; geology; aquifer properties; water quality; sediment load; land availability; monitoring; permits	Catchment-scale retention, groundwater support, drought and runoff-risk reduction

Source: Author's synthesis; technical checks should be refined using applicable standards and local investigations.

3.6 Monitoring Indicators for Pilot Implementation

A pilot project should be evaluated as a water-management system rather than only as a completed structure. Accordingly, the synthesis identifies a minimum monitoring set that can connect engineering performance to drought-adaptation outcomes. These indicators are presented in Table 3.

Table 3. Recommended Monitoring Indicators for Pilot Projects

Hydrology	Rainfall depth and event frequency	Quantify available source water and seasonal variability
RWH performance	Captured volume, tank level, overflow volume, demand offset	Assess storage reliability and direct-use benefit
Recharge performance	Infiltration rate, recharge duration, clogging/sediment condition	Verify whether the recharge structure remains hydraulically effective
Groundwater	Groundwater level before/after wet season; selected observation-well trends	Assess whether recharge and abstraction are moving toward a more resilient balance
Water quality	Turbidity and other parameters relevant to intended use; microbiological testing for potable applications; source-water quality before MAR	Prevent human-health risk and groundwater contamination
Operations	Cleaning frequency, first-flush function, filter condition, sediment removal, downtime	Measure maintenance adequacy
Socio-economic	Water purchase reduction, user acceptance, maintenance cost, responsible operator	Assess affordability and long-term institutional viability

Source: Author's synthesis based on RWH and MAR literature.

4. DISCUSSION

4.1 Why Integration Is Stronger Than a Stand-Alone Intervention

The proposed model improves on a stand-alone RWH approach by assigning a planned destination to overflow. A tank-only system can reduce demand effectively until storage is full or empty; its performance is therefore constrained at both ends of the seasonal cycle. Adding recharge converts at least part of wet-season excess into groundwater storage, where evaporation losses can be lower than in open surface storage and the resource may remain available beyond the immediate rainfall event. Conversely, a recharge-only program does not directly satisfy household or institutional demand at the point of capture. The combined model therefore allocates water according to two time horizons: immediate use and delayed subsurface storage.

This dual function is consistent with the international literature. Abd-Elaty et al. (2024) found that an integrated RWH–MAR strategy in an arid setting could increase modeled groundwater potential while managing flood runoff. Gebreslassie et al. (2025) similarly concluded that water harvesting and groundwater recharge should be treated as complementary components of sustainable water-resources management, particularly in arid and semi-arid regions. The conceptual contribution of the present study is to translate that system-level logic into a simple planning architecture suitable for staged implementation in NTT.

The model also provides a bridge between decentralized and centralized infrastructure. Household tanks do not replace reservoirs, dams, raw-water networks, or piped systems, and recharge trenches do not replace basin-scale water planning. Instead, distributed systems can reduce pressure on those larger assets by capturing rainfall near where it falls. This makes the model a complementary resilience measure rather than a substitute for conventional public water infrastructure.

4.2 Water Quality and Groundwater Protection as Design Constraints

Water quality is the most important safeguard preventing the model from being reduced to a simple "collect and infiltrate" strategy. Rooftop runoff may contain sediment, organic debris, microorganisms, metals, or pollutants deposited on catchment surfaces. Raimondi et al. (2023) show that first-flush quality and harvested-water characteristics depend on catchment material, environmental exposure, storage conditions, and treatment. Judeh et al. (2022) likewise demonstrate that smart RWH systems may require filtration, first-flush diversion, disinfection, and monitoring when higher-quality uses are intended.

The same principle is even more critical for artificial recharge because contaminants can be transferred into aquifers. Source water from relatively clean roofs is generally easier to control than runoff from roads, workshops, fuel-handling areas, or mixed urban drainage. The proposed model therefore places source selection, pre-treatment, and water-quality assessment before recharge. For larger MAR schemes, a hydrogeologic risk assessment should define the target aquifer, travel pathways, sensitive receptors, clogging potential, and monitoring locations. Sufyan et al. (2024) emphasize that MAR research and practice must balance water-quantity gains with water-quality protection.

From an engineering perspective, this requirement changes the project objective. The goal is not to maximize the infiltration rate under all conditions; it is to maximize safe, maintainable, and verifiable water conservation. A recharge facility that rapidly transmits contaminated runoff would be a failure even if its hydraulic capacity were high.

4.3 Technical Suitability and the Need for Site-Specific Design

The conceptual model is intentionally standardized at the process level and flexible at the structural level. A house on permeable soil with adequate groundwater separation may use a simple tank and infiltration well. A school on a larger site may combine modular tanks with several infiltration trenches. A settlement on low-permeability material may need lined storage, controlled reuse, or a different recharge location. A watershed-scale intervention may require infiltration basins or engineered MAR based on geophysical surveys and groundwater modeling. This flexibility is necessary because NTT contains diverse island geologies, slopes, soils, and settlement patterns.

The current Indonesian standard SNI 8456:2025 provides a formal technical reference for rainwater infiltration wells and trenches and should be consulted during design. The model adds value upstream of that design process by helping planners decide whether a recharge structure is appropriate, what source water will feed it, and how it connects to RWH storage and end use. This distinction is important: a standard can specify technical requirements for a structure, whereas the conceptual model specifies the water-management system within which the structure operates.

The screening equations proposed in the Methods section provide only a first-order water-balance logic. Reliable sizing still requires local rainfall time series, end-use demand profiles, runoff coefficients, tank simulation, infiltration testing, and groundwater data. For institutional or area-wide projects, sensitivity analysis should be performed for dry, normal, and wet years because a system optimized for average rainfall may fail to provide adequate drought resilience in dry years or adequate overflow capacity in extreme wet events.

4.4 Institutional Roles and Long-Term Operation

Technical feasibility alone is insufficient for long-term performance. Distributed water systems fail when gutters are not cleaned, first-flush devices are bypassed, storage tanks are left open, filters are not replaced, recharge structures clog with sediment, or no institution is responsible for monitoring. Therefore, governance is included as the fifth stage of the model rather than treated as a background condition.

Local government can provide enabling regulation, planning integration, incentives, public-facility demonstration projects, and coordination with drought-adaptation and disaster-risk-reduction programs. Universities can support site surveys, prototype development, water-quality testing, monitoring, student fieldwork, and community training. Facility managers and communities are essential for daily operation and maintenance. Private-sector and non-governmental partners can contribute materials, financing, technical innovation, or corporate social responsibility support. This distribution of roles is particularly suitable for NTT because implementation will likely be incremental and geographically dispersed rather than delivered through a single large project.

A practical policy pathway would begin with public buildings because they combine large roof catchments, identifiable operators, and educational visibility. Schools, campuses, health facilities, government offices, and places of worship can function as monitored demonstration sites. Performance data from these sites could then support technical guidelines, cost benchmarks, and replication packages for households and communities.

4.5 Research Contribution, Limitations, and Future Agenda

The scientific contribution of this study is a context-specific integration framework rather than a new hydraulic equation or empirical performance estimate. It synthesizes the drought context of NTT with contemporary RWH and MAR knowledge and converts that synthesis into a five-stage model, a three-scale implementation structure, screening criteria, and a monitoring framework. This makes the concept more operational than a general recommendation to "harvest rainwater" or "build infiltration wells."

However, the absence of field data is a major limitation. The model has not yet been validated against a specific roof catchment, village water balance, infiltration test, groundwater hydrograph, or water-quality dataset in NTT. It therefore cannot support claims about exact drought-duration coverage, recharge volume, groundwater-level increase, or cost savings. These quantities must be established empirically.

Future research should proceed through a sequence of pilot studies. First, select representative sites across different NTT hydrogeologic and settlement contexts. Second, collect daily rainfall, roof area, end-use demand, infiltration, groundwater-level, and baseline water-quality data. Third, simulate tank performance and overflow under multiple climate years. Fourth, design recharge structures according to SNI requirements and hydrogeologic suitability. Fifth, monitor captured volume, demand offset, recharge behavior, water quality, operation cost, and user acceptance for at least one complete wet–dry seasonal cycle. Larger schemes should additionally use groundwater modeling and cost–benefit analysis. This progression would convert the current conceptual contribution into a validated engineering decision-support framework.

5. CONCLUSION

Drought adaptation in East Nusa Tenggara requires better management of the seasonal relationship between wet-season rainfall and year-round water demand. The evidence reviewed in this study indicates that the province's drought problem is recurrent, spatially variable, and influenced by both climatic and land-surface factors. A strategy based only on emergency water supply during the dry season does not address the underlying loss of wet-season water through unmanaged runoff.

This study therefore proposes an integrative rainwater harvesting–artificial recharge model structured around five stages: capture, store, use, recharge, and govern. Rainwater harvesting provides an immediate decentralized water reserve and reduces demand on conventional sources, while artificial recharge provides a pathway for controlled surplus to support groundwater conservation. The model is designed for household, institutional, and area-wide implementation and is strengthened by explicit screening criteria for rainfall, demand, runoff, infiltration, groundwater depth, source-water quality, contamination risk, and maintenance capacity.

The model should be treated as a planning framework rather than a final engineering design. Its practical value will depend on pilot validation, compliance with applicable standards, site-specific hydrogeologic investigation, water-quality protection, and long-term monitoring. With these safeguards, the integrated approach can become a replicable complement to larger water-resource infrastructure and can support a transition from drought response toward proactive seasonal water resilience in East Nusa Tenggara.

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AUTHOR CONTRIBUTIONS

The author was solely responsible for the conceptualization of the study, research design, literature collection and synthesis, development of the integrative rainwater harvesting–artificial recharge model, formulation of the screening and monitoring frameworks, interpretation of the findings, preparation and visualization of the conceptual model, manuscript writing, 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 new empirical dataset was generated in this conceptual review. The study is based on published literature, technical standards, and institutional sources cited in the manuscript.

ETHICAL STATEMENT

This conceptual review did not involve human participants, animals, or collection of identifiable personal data; therefore, research ethics approval was not required for the literature-synthesis component.

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