Limiting Factors Affecting the Efficiency of Rainwater Harvesting in Karst Telaga Systems: A Case Study in Gunungkidul, Indonesia

Tri Budi Utama
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
tribudi@student.ub.ac.id

M. Bisri
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
mbisri@ub.ac.id

Tri Budi Prayogo
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
tribudip@ub.ac.id

Riyanto Haribowo
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
riyanto_haribowo@ub.ac.id

Lily Montarcih Limantara
Department of Water Resources, Faculty of Engineering, University of Brawijaya, Indonesia
lilymont@ub.ac.id (corresponding author)

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ABSTRACT

This study evaluates the dominant limiting factors that affect the efficiency of Rainwater Harvesting (RWH) systems in karst telaga environments of the Semanu and Tepus districts, Gunungkidul, Indonesia. A structured analytical framework was developed based on three interrelated system components—harvesting, storage, and utilization—to assess both theoretical and actual system performance. Field measurements from 40 telaga lakes were integrated with climatological, hydrological, and geological data to quantify performance gaps and identify dominant loss mechanisms. The results indicate a substantial discrepancy between the theoretical harvesting potential (20.85%) and actual system efficiency (6.09%). High infiltration rates associated with karst characteristics significantly reduce effective runoff, while evaporation losses of 5–7 mm/day and average sedimentation levels of 48.25% decrease storage capacity to approximately 35% of its initial design. In addition, distribution inefficiencies further constrain effective water utilization for irrigation. These interacting loss mechanisms collectively limit storage duration to only 2–3 months after the rainy season. By systematically linking empirical findings to parameter prioritization, this study provides a structured analytical model for diagnosing efficiency gaps in karst-based RWH systems. The findings support targeted optimization strategies focused on loss reduction, storage rehabilitation, and distribution improvement. The proposed framework contributes a replicable approach for evaluating rainwater harvesting efficiency in tropical karst regions facing seasonal water scarcity.

Keywords-rainwater harvesting; system efficiency; storage capacity; evaporation; karst area; Gunungkidul

I. INTRODUCTION

The Gunungkidul Regency is one of the areas in Indonesia with relatively high annual rainfall, that is, between 1,500 and 2,200 mm per year [1]. However, the availability of water resources in this area is very limited due to the geological characteristics of karst, through which the rainfall permeates the limestone fractures very quickly [2]. The high level of infiltration causes water to not last long, making it difficult for society to obtain a sustainable water supply, especially during the dry season [3-4].

The limitation of water is also aggravated by the status of Gunungkidul, as there is no large aquifer to store groundwater in sufficient amounts [5]. This condition causes society to be very dependent on Rainwater Harvesting (RWH) through telaga lakes and small dams that have long been utilized as the main source of domestic water and irrigation [6]. Although the conventional RWH system has been widely researched, its effectiveness still faces various technical constraints. The high evaporation rate on a telaga surface can cause water losses of up to 30–50% per year. In addition, the sedimentation due to the erosion from the catchment area is gradually decreasing the storage capacity, so the water supply is increasingly limited from year to year [7]. Besides the technical factors, the effectiveness of RWH is also influenced by the social aspect, mainly the pattern of utilization and water distribution. Non-optimal management often causes the stored water to be inefficiently distributed into agricultural land, thus farmers still experience water deficit during long dry seasons [6, 8].

This research aimed to investigate the main factors that influence the efficiency of RWH in the karst area of the Tepus district, Gunungkidul, focusing on the effects of infiltration, evaporation, and sedimentation on storage capacity and water availability. This research also evaluates how far the telaga systems can support the demand for dry-land agriculture and develops an optimization strategy to make the RWH more adaptive to the hydrological challenge in the karst area. This study aimed to offer a more comprehensive understanding of the dynamics of RWH in the karst area. From the practical side, the findings can be used as a reference in managing water resources to increase storage capacity and distribution efficiency in the agricultural sector. Meanwhile, from the policy side, this research can help with basic planning of water conservation and strengthen the resilience of agricultural water in the Gunungkidul area.

Rainwater harvesting also plays a strategic role in mitigating land degradation and desertification processes in semi-arid regions. By capturing and storing seasonal rainfall, RWH systems help maintain soil moisture, support vegetation cover, and reduce erosion during prolonged dry periods. In karst landscapes where natural surface retention is limited, effective water harvesting contributes to ecological resilience and stabilizes agricultural land use.

Recent studies on RWH have emphasized that system performance is strongly influenced by hydrological, geological, and operational variables. In semi-arid and karst environments, infiltration losses, open storage evaporation, sedimentation, and inefficient distribution have been identified as the main constraints that limit effective storage capacity and water reliability. Several studies in Indian, African, and Mediterranean karst regions have demonstrated substantial discrepancies between the theoretical runoff potential and the actual usable storage due to interacting loss mechanisms. However, most previous research evaluated these factors independently, without integrating them into a structured system-based analytical framework that captures their combined impact on overall efficiency.

Despite the growing body of research on RWH, a limited number of studies systematically quantified the relative influence of infiltration, evaporation, sedimentation, and distribution inefficiencies within a unified harvesting-storage-utilization framework, particularly in tropical karst regions. In the case of Gunungkidul, previous studies have focused mainly on water availability, hydrochemistry, or socio-hydrological aspects, rather than providing an integrated efficiency assessment model capable of identifying dominant limiting factors.

This study addresses this gap by developing a structured analytical model that evaluates RWH efficiency through component-based system analysis and parameter prioritization. By linking empirical measurements from 40 telagas to a dominant-factor identification approach, this research moves beyond descriptive assessment and provides a reproducible analytical framework for diagnosing performance gaps and formulating targeted optimization strategies in karst-based RWH systems.

II. MATERIALS AND METHODS

A. *Research Location and Time*

The case study was conducted in Semanu and Tepus districts, Gunungkidul, Yogyakarta, at 40 RWH telagas on dry agricultural land that uses the conventional agricultural system. The research period was during the dry season for understanding the patterns of water availability without inflow from rainfall. Figure 1 presents the research location.

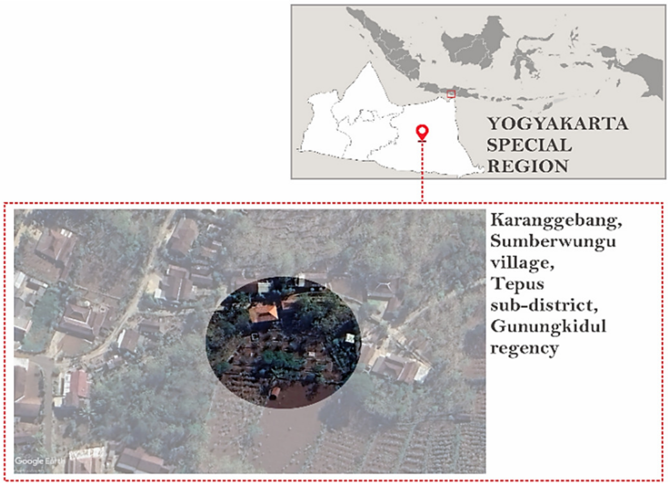

Fig. 1. Research location.

The dominant soil types in the study area consist of shallow calcareous soils with sandy-loam to loamy textures overlaying limestone bedrock. The relatively coarse texture and high permeability contribute to rapid infiltration and limited surface retention. These soil characteristics further influence runoff generation and groundwater percolation dynamics within the telaga catchment areas.

B. Data Collection

The primary data consists of: (i) Measurement of the water storage capacity in telagas; (ii) Observation of evaporation and sedimentation level; and (iii) Interviews with farmers about the utilization of rainfall for agriculture. The secondary data consists of: (i) Rainfall data from BMKG; (ii) Geological and topographic maps in the research location; (iii) Geological and hydrological supporting data, sourced from regional water resource agencies. Field measurements were conducted independently by the research team during the study period to ensure data reliability and consistency.

C. Steps of Analysis

To address the limitations of descriptive assessment, this study adopts a structured analytical framework that conceptualizes RWH performance as the interaction of three interdependent system components:

1. Harvesting component – runoff generation and inflow.
2. Storage component – effective retention capacity.
3. Utilization component – distribution efficiency and usable supply.

This framework enables the identification of performance gaps between theoretical runoff potential and actual effective storage.

This research combines secondary and primary data analysis to identify the main factors that influence the efficiency of RWH in the karst area in the Tepus District, Gunungkidul. Secondary data include information on climatology, hydrology, geology, and historical data related to water storage capacity, level of infiltration, evaporation, and sedimentation. Primary data is obtained through a field survey for understanding the actual condition of telagas and interviews to determine how telaga water is utilized for agriculture and other needs. The method applied in this research is as follows.

1) Analysis of Factors that Influence the Efficiency of Rainfall Harvesting

This analysis is carried out using secondary data from BMKG, the Ministry of PUPR, and previous research results related to climatology, hydrology, and geology aspects in the karst area of Gunungkidul [9-11]. The data used consists of: (i) annual rainfall and its distribution throughout the year to determine the availability of rainfall that can be utilized, as investigated in [1, 12]; (ii) The run-off coefficient and the characteristics of land use to understand the pattern of water absorption in the research area, as investigated in [13-14]; (iii) Hydrology data related to surface water flow patterns and storage capacity of telagas and small dams, as investigated in [15-16]. The field survey was carried out to determine the actual condition of the telaga, including the physical condition, storage area, and the water flow patterns in the surrounding research location. Interviews were carried out with the society in the surrounding telaga to determine the use of rainfall that is stored for agriculture, as well as domestic or other demands.

2) Influence of Infiltration, Land, Evaporation, and Sedimentation on Storage Capacity and Water Availability

The analysis of land infiltration involved: (i) Secondary data related to land infiltration, obtained from previous geological and hydrological research that discussed the characteristics of soil porosity in Gunungkidul [9, 17]; (ii) Data related to the geology map, research report on water infiltration in the karst area, and data on the velocity of water absorption in the soil in several zones [3, 18, 19]; (iii) A field survey carried out to observe signs of water loss due to infiltration such as cracks in the telaga bed or water losses in the short time after rainfall [20].

3) Measurement of Water Losses Due to Evaporation

The analysis of evaporation was carried out using secondary data from BMKG and related hydrology research [21]. The data consists of (i) Air temperature, relative humidity, wind velocity, and sun radiation, which are the main factors in the evaporation process [21]; (ii) Research reports on evaporation rates in telagas and small dams in Gunungkidul to determine the patterns of water losses due to evaporation, as investigated in [3, 6, 7]. The analysis was carried out using Penman-Monteith, which is frequently used in evaporation studies in tropical areas to predict the water losses due to evaporation from the water storage surface, as investigated in [10, 21-24]. Field observation was carried out to record the physical condition of the telaga water surface; for instance, the availability of water vegetation that can reduce evaporation, or water pollution levels that can influence the evaporation process.

4) Evaluation of the Impact of Sedimentation on Water Storage Capacity

Secondary data related to telaga and small dam storage capacity were obtained from a regional government report, a hydrology study, and a previous study on sedimentation in the water storage system in Gunungkidul [25, 26]. The data used consist of: (i) Comparison of water storage depth in several recent years to determine the sedimentation rate, investigated in [27]; (ii) Analysis data of water quality and turbidity level showing the level of sediment material in the water storage, as investigated in [8, 28]. A field survey was carried out to observe the sedimentation condition in the telaga bed, for instance, the availability of thick mud or a change in water color that indicates a high sediment content [29].

5) System Optimization Strategy for Rainwater Harvesting

The aim was to analyze the factors that influence the efficiency of RWH and to provide an optimization strategy to increase the effectiveness of the system in supporting the agriculture of dry land. This strategy involved: (i) Analysis of policy and recommendations of previous research related to the management of RWH in the karst area, as investigated in [2, 8, 18, 26, 30]; (ii) A method to evaluate the increase in storage capacity due to sediment dredging and the expansion of the catchment area [14, 15, 31]; (iii) The effectiveness of evaporation decrease technology, such as the use of floating cover and protection vegetation [11, 17, 32]; (iv) Analysis of more efficient water distribution methods, including drip irrigation and gravitation based systems [4, 33, 34].

D. Definition of Efficiency Metrics

Two efficiency indicators were defined to quantify system performance:

- Theoretical efficiency (η_t) is estimated using the rational method:

  $$Q = C \cdot I \cdot A$$

where Q is runoff discharge, C is the runoff coefficient, I is the rainfall intensity, and A is the catchment area. Theoretical efficiency represents the potential runoff relative to design storage capacity. (η_t: storage/Q).

- Actual efficiency (η_a) is defined as the ratio between the effective stored water volume and the theoretical runoff potential.

  The performance gap is quantified as:

  $$Performance\ Gap = \eta_t - \eta_a$$

This metric forms the basis for identifying dominant limiting factors.

E. Loss Mechanism Quantification

To determine system constraints, four primary loss mechanisms were quantified:

- Infiltration loss due to karst percolation.
- Evaporation loss, estimated using daily evaporation rates.
- Sedimentation-induced reduction in effective storage capacity.
- Distribution inefficiency within irrigation channels.

Each mechanism was evaluated in terms of its contribution to effective storage reduction.

F. Dominant-Factor Identification Procedure

A structured prioritization procedure was applied:

- Classification of parameters into harvesting, storage, and utilization variables.
- Quantification of each loss mechanism.
- Sensitivity-based comparison of parameter magnitude relative to total performance gap.
- Ranking of dominant factors based on system impact.

This approach ensures a systematic link between empirical measurements and analytical conclusions.

G. Strategy Derivation Logic

Optimization strategies were derived analytically from the dominant-factor ranking. Each intervention corresponds directly to a specific loss mechanism:

- High sedimentation → storage rehabilitation and desilting.
- High evaporation → reduction of exposed surface area.
- High infiltration → percolation control measures.
- Distribution inefficiency → improved micro-irrigation control.

This structured mapping ensures transparency, replicability, and empirical grounding of the proposed strategies.

III. RESULTS AND DISCUSSION

A. Determination of Factors on the Efficiency of Rainwater Harvesting

The analysis of the 40 telagas in Semanu and Tepus districts shows that the efficiency of the RWH system is determined by the interaction between three main components: harvesting, storage, and utilization of rainfall. These three components are simultaneously influenced by climate dynamics, characteristics of the karst hydrology, the physical condition of the telaga, and the effectiveness of the water distribution system.

Comparable discrepancies between theoretical and actual efficiency have been reported in karst-based RWH systems in India, China, and the Mediterranean, where subsurface leakage, evaporation, and sedimentation strongly constrain effective storage [35, 36]

The analytical framework reveals a substantial discrepancy between the theoretical harvesting potential and the actual performance of the system. Theoretical efficiency (20.85%) was estimated based on rainfall intensity, catchment area, and runoff coefficient. However, actual efficiency was measured at only 6.09%, indicating a significant performance gap. This gap confirms that runoff generation alone does not determine system reliability. Instead, post-harvesting loss mechanisms critically constrain effective storage capacity.

The quantitative evaluation shows that the effectiveness of actual harvesting varies across telagas, and it is generally still well below the theoretical potential. Figure 2 presents the effectiveness of rainfall harvesting.

Using the parameter prioritization framework described in the methodology, loss mechanisms were ranked according to their relative contribution to performance reduction:

1. Sedimentation (capacity reduction)
2. Infiltration (karst percolation)
3. Evaporation
4. Distribution inefficiency

Sedimentation emerged as the most significant structural constraint, followed by geological infiltration losses. Evaporation and distribution losses act as reinforcing mechanisms that accelerate storage depletion. This ranking provides an analytical basis for targeted intervention rather than generalized improvement strategies.

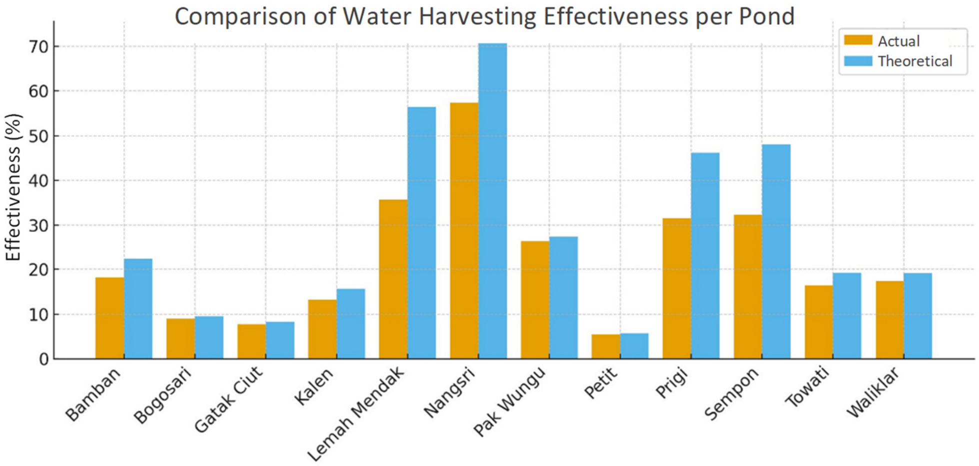

Fig. 2. Effectiveness of rainfall harvesting.

B. Dynamics Influence of Climatology and Evaporation

The research area has a seasonal rainfall pattern, with high rainfall in short duration and a relatively long dry season. This condition causes the surface run-off to occur in an episodic manner, while water losses due to evaporation occur continuously. These magnitudes are consistent with reported evaporation losses of 1,800–2,500 mm/year in open reservoirs across semi-arid regions of South Asia and East Africa [37, 38]

Based on the evaporation analysis (using the Penman-Monteith method): (i) The evaporation rate of the water surface is between 5 and 7 mm per day; (ii) Water losses during the dry season are equivalent to 26 and 65% of the telaga capacity; (iii) Annual losses on several telagas reach more than 80% of the storage capacity. Figure 3 presents the percentage of evaporation to the telaga capacity. More than half of the telaga are over the critical crest of 50% seasonal as well as annually, including the telagas of Kalen, Lemah Mendak, Bamban, Progi, and Sempon. This condition explains why most telagas can supply water only during 2–3 months after the rainy season, as recorded on the storage duration data of the field survey results. Figure 4 presents the duration of telaga storage.

C. The Infiltration Influence of Karst on the Harvesting Process

The characteristic of karst in Gunungsewu is that it is dominated by cracks; a sub-surface flow system causes the infiltration to happen very fast, so most of the rainfall becomes surface run-off. This is reflected from the field data that are as follows: (i) 15 telagas (37.5%) have actual harvesting effectiveness of 0%; (ii) Some telagas with catchment areas more than 100,000 m^2 do not yet produce effective storage; (iii) Telagas without an impermeable bed layer show that the water losses are very fast through percolation. The extreme example is seen on the telagas of Petit/ dedel Wetan, Gatak Ciut, and Pak Wungu, which, due to their morphometry, have the potential to store water but cannot maintain the water volume. This finding confirms that the efficiency of RWH in the karst area is very influenced by the sub-surface hydrology process and not only by the storage size.

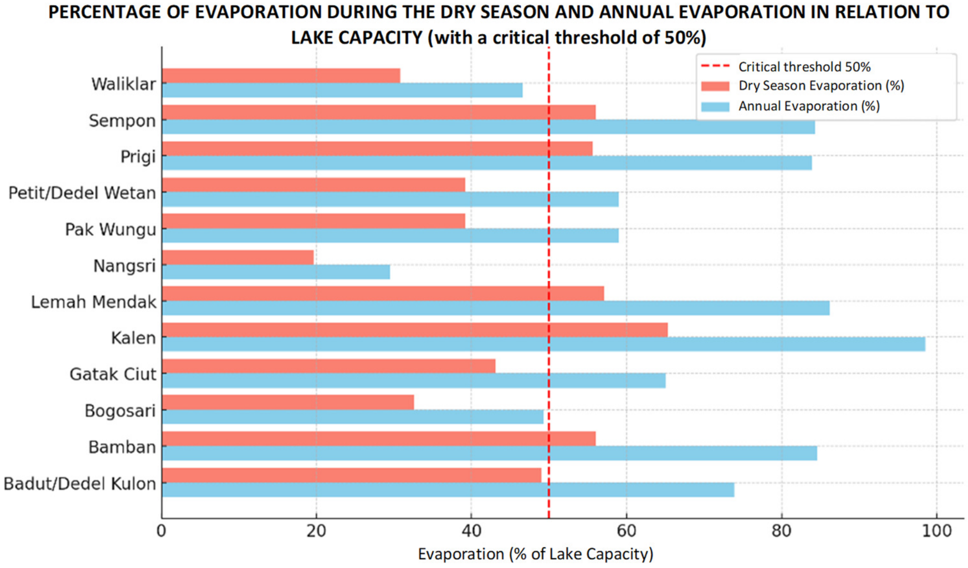

Fig. 3. Percentage of evaporation to the telaga capacity.

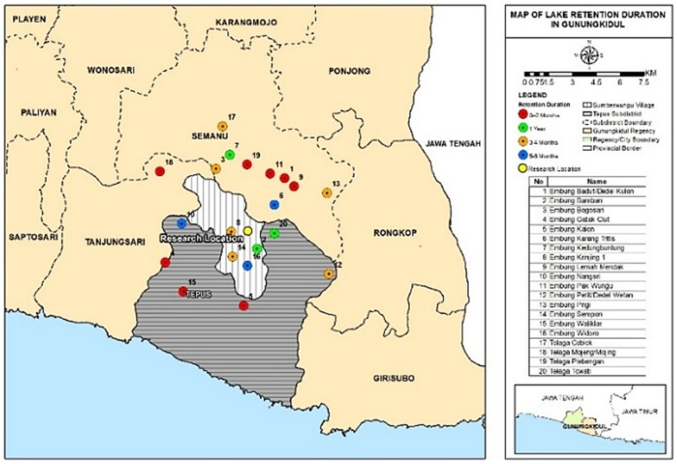

Fig. 4. Duration of telaga storage.

D. *Degradation of Storage Capacity Due to Sedimentation*

The survey results show that sedimentation is a main factor in the decrease in storage capacity. Quantitatively, the results are as follows: (i) The average sedimentation of telagas reaches 48.25%; (ii) The actual capacity is still about 35% of design capacity; (iii) 50% of telagas experience sedimentation more than 50%; (iv) Some telagas experience full sedimentation (100%), which have been changed into agricultural area. Figure 5 presents a map of the sedimentation level of telagas.

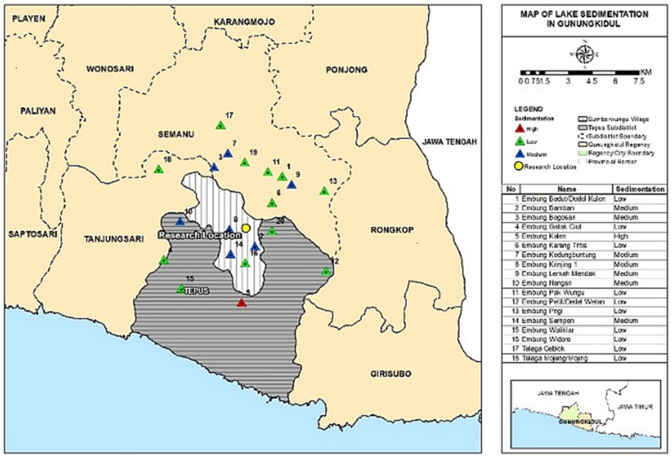

Fig. 5. Map of telaga sedimentation levels.

The higher sedimentation is recorded on the telagas of Kalen (70%), Bamban (50%), Karang Tritis (50%, and Bogasari (50%). The direct impact of sedimentation is the decrease of storage volume and the increase of the ratio between surface area and volume, which then accelerates the water losses due to evaporation.

Inefficient water allocation and the lack of crop-specific irrigation scheduling further reduce effective utilization. Comparable studies demonstrate that without pressurized or drip irrigation systems, water productivity in smallholder agriculture remains substantially below potential levels [39].

E. *The Effectiveness of Distribution and Water Utilization Patterns*

All telagas that are still functional are utilized for agriculture (100%), with additional activities for fishery (±60%), husbandry (±40%), and household water (±30%). However, the water distribution system is still dominated by land channels and simple pumps. Based on the field survey and interviews: (i) Water losses on the distribution system are estimated at about 30–40%; (ii) Water utilization has not been customized with the efficiency of crop demand; and (iii) Water often runs out before reaching the critical phase of crop growth.

The limited accumulation on the aspects of harvesting, storing, and distribution causes the effectiveness of average actual harvesting to be only 6.09%, which is much lower than the theoretical effectiveness of 20.85%, as shown in the comparison graphic of the effectiveness of telagas (Figure 2).

F. *Efficiency Optimization Strategy of Rainfall Harvesting*

Based on the quantitative results and field observations, an increase in RWH efficiency can only be reached through an integrated approach that involves all components of the system.

1) *Recovery of Storage Capacity and Catchment Area*

Due to the average sedimentation on 48.25%, the priority steps are as follows: (i) Sediment dredging on telagas with sedimentation of more than or equal 50%; (ii) Development of sand traps and inlet improvements; (iii) Strengthening connectivity in the catchment area; (iv) Re-vegetation of slopes for decreasing the sediment supply.

2) *Decrease in Water Supply Due to Evaporation*

Telagas with evaporation losses of more 50% require: (i) Drip irrigation or pipes with low pressure; (ii) Decrease of inundation surface area; and (iii) Application of floating cover or limitation of protected vegetation.

3) *Optimization of Water Distribution for Agriculture*

Utilization efficiency can be increased through: (i) Drip irrigation or low-pressure pipes; (ii) Secondary storage basins for regulating the group distribution; and (iii) Regulation of time and volume of water collection based on crop requirements.

4) *Percolation Control on the Karst Telaga*

In telagas with very fast water losses, technical tests are needed: (i) Linear geo-membrane or clay blanket on the telaga bed; and (ii) Combination of opened telaga with small-scale closed storage.

5) *Synthesis of Performance Gap on the RWH System*

The lower RWH efficiency in the research location is caused by three main mechanisms that are mutually reinforcing as follows: (i) Sedimentation that decreases the storage volume until almost half of the initial capacity; (ii) High evaporation that causes seasonal and annual water losses, which is more than critical; (iii) Infiltration of karst and inefficient distribution, where stored water is quickly lost before being utilized.

IV. CONCLUSION

This research shows that the efficiency of RWH in the 40 telagas in the Semanu and Tepus districts is very low and cannot optimally support agricultural water needs. The main factors causing low system performance consist of: (i) The decrease in storage capacity due to the average sedimentation is 48.25%, so the effective volume is only about 35% of design capacity; (ii) The effectiveness of RWH is very low, with a theoretical value of 20.85% and an actual value of 6,.09%, while 15 telagas do not contribute to storage; (iii) high evaporation (5–7 mm/day) causes daily water losses of 31–43 m^3, accelerating the decrease of volume in the dry season; (iv) Water retention is short and only endures 2–3 months, so it cannot fulfil the irrigation requirement during the dry cropping season. Overall, the existing RWH system has not been an effective agricultural water source in the dry-karst area.

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