JPPIPA 12 (7) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Water Balance Analysis and Embung-Long Storage Planning as a Technical Irrigation Solution for Rainfed Paddy Fields in Padang Kunik Village, Kuantan Singingi Regency

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Received: April 25, 2026
Revised: June 21, 2026
Accepted: July 25, 2026
Published: July 31, 2026

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DOI: 10.29303/jppipa.v12i7.15850

Open Access

Abstract: Rainfed paddy fields relying entirely on rainfall are vulnerable to seasonal water deficits and limited to one planting season per year (Cropping Index/CI 100). This study analyzed the water balance of 77 ha of rainfed paddy land in Padang Kunik Village, Kuantan Singingi Regency, and formulated a technical storage solution to improve irrigation water availability. Water availability was calculated using the Simple Water Balance method with 20 years of rainfall data (2006–2025) from three rain gauges, while irrigation demand followed KP-01 guidelines. The Ripple (mass-curve) method determined the required Effective Storage Capacity. Results showed deficits in seven separate periods, with a cumulative peak deficit of 140,647.00 m³ in April I and a total required storage volume, after accounting for evaporation, seepage, and sediment losses, of 175,077.41 m³. A combination of an embung (172,800.00 m³ on 4.3 ha of non-productive land) and 4,562 m of long storage was planned, yielding a total volume of 177,362.00 m³, or 101% of the requirement, distributable to the paddy fields by gravity given the elevation difference. The proposed system is technically feasible to eliminate seasonal deficits and could raise the Cropping Index from CI 100 to CI 200.

Keywords: Embung; Irrigation deficit; Long storage; Rainfed paddy fields; Water balance

Introduction

Irrigation is a primary determinant of rice production success; however, in rainfed paddy fields, water availability depends entirely on rainfall without storage infrastructure support (Erythrina et al., 2021). Changing rainfall patterns due to climate variability increasingly raise the risk of water deficits in rainfed areas and reduce agricultural productivity (Parwin et al., 2023), a pattern consistent with long-term rainfall variability documented across Sumatra (Marzuki et al., 2025) and with the water-use efficiency challenges reported for other rainfed rice systems in Indonesia (Mahrup et al., 2005). This condition occurs on 77 ha of rainfed paddy fields in Padang Kunik Village, Kuantan Singingi Regency, which can only achieve one planting season per year (CI 100) due to the absence of water storage infrastructure. A prior study at the same location identified this deficit through a macro-level water balance assessment but stopped short of formulating an engineered storage solution (Nulfi, 2023). Sound water balance management, including the use of surplus water during the wet season to offset deficits in the dry season, is key to the sustainability of rainfed irrigation systems (Acevedo et al., 2022), an approach also used to optimize planting patterns and calendars for rainfed paddy cultivation elsewhere in Indonesia (Yoga & Simanjuntak, 2024).

Various efforts to improve water availability in rainfed areas have been studied elsewhere, including through soil and water management optimization (Acevedo et al., 2022), reservoir-based water allocation

How to Cite:
Darma, D. M., Wahyuni, S., & Prayogo, T. B. (2026). Water Balance Analysis and Embung-Long Storage Planning as a Technical Irrigation Solution for Rainfed Paddy Fields in Padang Kunik Village, Kuantan Singingi Regency. *Jurnal Penelitian Pendidikan IPA*, *12*(7), 356–367. https://doi.org/10.29303/jppipa.v12i7.15850

in watersheds (Ariyanto, 2022), and rainwater-harvesting embung systems that support agricultural productivity in rainfed land (Setyandhinavia et al., 2025). Storage solutions in the form of an embung and long storage are considered most appropriate for locations where the upper catchment has hilly topography but the paddy fields themselves lie on the relatively flat valley floor, such as in Padang Kunik Village, consistent with the scaling-up practices for rainfed embungs reported by Sudianto et al. (2024). The novelty of this study relative to the prior assessment lies in moving beyond identification of the existing deficit toward a full technical design: quantifying the Effective Storage Capacity through the Ripple method and dimensioning an implementable combination of an embung and long storage that also accounts for evaporation, seepage, and sediment losses in the storage-volume requirement. Based on the foregoing, this study aimed to analyze the existing water balance condition, namely irrigation water availability and demand on rainfed paddy fields of Padang Kunik Village throughout the cropping period, and to formulate the most effective technical alternative solution to improve water availability and irrigation efficiency at the site.

Methods

This study was conducted on 77 ha of rainfed paddy fields in Padang Kunik Village, Kuantan Singingi Regency. Twenty years of rainfall data (2006–2025) from Koto Baru Station, Muara Lembu Station, and Lubuk Ramo Station were processed into areal rainfall using the Thiessen Polygon method. Data consistency was tested through double mass curve analysis, trend absence testing using the Spearman method, stationarity testing using F-Test and T-Test, and persistence testing, all of which confirmed the data were suitable for water balance analysis. Potential evapotranspiration was calculated using the Penman method (Penman, 1948), while irrigation water demand per cropping period was calculated following KP-01 guidelines, consistent with CROPWAT-based crop water requirement approaches applied elsewhere in Indonesia (Suryadi et al., 2019), accounting for crop consumptive use, percolation, and land preparation.

Water availability was analyzed using the Simple Water Balance method (Jonizar & Martini, 2017; Almeida et al., 2024) to obtain the water balance for each bi-monthly period over one hydrological year (December–November); inflow in this analysis corresponds to effective rainfall over the paddy-field catchment area (DTA) itself, consistent with the site's complete dependence on rainfall rather than a perennial river source, an approach consistent with catchment-based baseflow and environmental-flow characterization used for other Indonesian sub-watersheds (Sodikin et al., 2025) and with rainfall-runoff modeling validated for data-scarce Indonesian catchments (Putri et al., 2025). The effective storage capacity (ESC) required to cover water deficits was determined using the Ripple method (cumulative mass curve), which compares cumulative inflow and outflow each period, accounting for the use of surplus water from previous periods to cover deficits in subsequent ones.

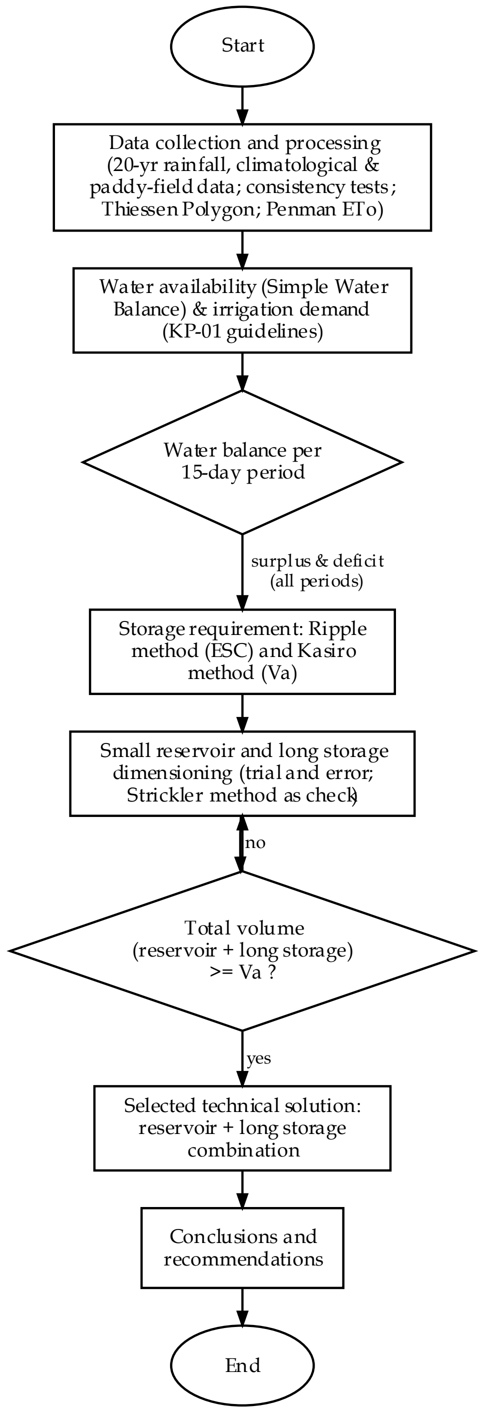

Figure 1. Research methodology flowchart

The required storage volume (Va) was then obtained using the Kasiro (1997) method, which adds evaporation, seepage, and sediment-accumulation allowances to the ESC-based demand volume, so that these losses are already incorporated in the storage design, consistent with embung design practice that accounts for evaporation and sediment losses in tropical settings (Harits et al., 2025) and with the proportional contribution of evaporation and seepage losses to on-farm reservoir outflow reported elsewhere (Panigrahi et al., 2007; Agrawal et al., 2004). Embung dimensions were determined through trial and error across land area variations from 4.7 ha to 1.0 ha at 0.1 ha intervals, following the Director General of Water Resources Circular Letter No. 07/SE/M/2021, with a fixed storage depth of T = 4.0 m in each scenario. Long storage volume was computed primarily as static storage (cross-sectional area × length); the Strickler method was then applied only as a supplementary check to confirm the resulting cross-section could also convey the design discharge without overtopping. The final technical solution was selected by comparing the ability of the embung and long storage combination to meet the total storage requirement (Va) during critical periods. The overall research workflow is summarized in Figure 1.

Results and Discussion

Existing Water Availability and Demand

Areal rainfall from the Thiessen Polygon weighting showed unequal contributions from the three observation stations, with Lubuk Ramo Station providing the largest weight (54.31%) and the highest mean rainfall (56.21 mm), followed by Muara Lembu Station (37.12%; 43.48 mm), and Koto Baru Station (8.57%; 10.28 mm). The dependable rainfall (Q80) derived from this data varied throughout the year following seasonal patterns, ranging from 16.758 mm in September I to 120.913 mm in December II. The June–September period showed the lowest mean Q80 (33.05 mm) as the peak dry season, while the October–April period showed the highest mean Q80 (65.98 mm) as the wet season, a pattern consistent with Sumatra's regional climate. On the demand side, the reference evapotranspiration (ETo) calculated using the Penman method ranged from 3.35–4.34 mm/day, with the highest value occurring in April I (4.34 mm/day), coinciding with the early growth phase of rice, which further amplified irrigation water demand during that period.

The existing cropping pattern in Padang Kunik Village is Rice–Secondary Crop (CI 100), with the rice planting season starting in December II (land preparation) through April I (harvest), followed by secondary crops (maize) in July II. Net Field Requirement (NFR) and Diversion Requirement (DR) were calculated following KP-01 guidelines. As an example, for the January II period:

$$\text{Total Water Demand} = ETC + IR + \text{Percolation} + WLR \quad (1)$$

$$\text{Total Water Demand} = 0.969 + 8.775 + 0.000 + 0.278 = 10.022 \text{ mm/day}$$

$$NFR = (10.022 - 2.835) \times (10{,}000/86{,}400) = 0.832 \text{ l/s/ha} \quad (2)$$

$$DR = NFR / 0.65 = 0.832/0.65 = 1.280 \text{ l/s/ha} \quad (3)$$

Peak Water Demand

The volume of water demand per period was obtained from DR × Area × Duration (15 days). In the January II period, water demand reached 127,706 m^3 (the annual peak) coinciding with the land preparation phase. Water availability during the same period was 44,064 m^3, far below demand, resulting in the largest deficit in the existing water balance of 83,642 m^3. Water availability was calculated using the Simple Water Balance method.

$$Ka = 0.0116 \times (r - ETo) \times A \quad (4)$$

Example Dec I:

$$Ka = 0.0116 \times (66.44 - 3.94) \times 0.7715 = 0.037 \text{ m}^3/\text{s} = 47{,}952 \text{ m}^3$$

Based on the calculations in Table 1, of the 24 total periods in a year, 17 periods had surplus status and 7 periods had deficit status. Deficits occurred in seven separate periods — January I, January II, February I, March I, March II, April I, and July II — interrupted by a surplus in February II (+5,028 m^3), so the sequence is concentrated in, but not strictly continuous through, the land preparation and early vegetative window. The largest deficit occurs in the January II period at −83,642 m^3, coinciding with the highest annual water demand of 127,706 m^3, which represents the land preparation period requiring a very large volume of water for soil saturation and paddy field inundation. Other significant deficits also occur in the March I period (−55,102 m^3) and March II period (−53,364 m^3), indicating that the early vegetative phase of the rice crop with high water requirements is still ongoing. In addition, there is one supplementary deficit period in July II at −12,492 m^3, occurring amid a series of surplus periods and indicating additional water requirements related to secondary crop maintenance that are not offset by water availability during that period. Cumulatively, the total cumulative deficit of −290,359 m^3 across these 7 periods demonstrates that the existing water supply system is unable to optimally meet all irrigation water requirements under the Rice–Secondary Crop cropping pattern, thereby necessitating water storage infrastructure to cover deficits during critical periods (Jonizar & Martini, 2017). Details of the existing water balance for each period are presented in Table 1 below.

Table 1. Existing water balance for rice–secondary crop cropping pattern

Month	Period	Water availability (m^3)	Water demand (m^3)	Water balance (m^3)	Status
Dec	I	47,952	-	47,952	S
	II	84,240	-	84,240	S
Jan	I	54,432	93,675	-39,243	D
	II	44,064	127,706	-83,642	D
Feb	I	41,472	75,533	-34,061	D
	II	45,360	40,332	5,028	S
Mar	I	29,808	84,910	-55,102	D
	II	27,216	80,580	-53,364	D
Apr	I	27,216	39,671	-12,455	D
	II	89,424	-	89,424	S
May	I	46,656	-	46,656	S
	II	49,248	-	49,248	S
Jun	I	38,880	-	38,880	S
	II	15,552	-	15,552	S
Jul	I	19,440	-	19,440	S
	II	18,144	30,636	-12,492	D
Aug	I	12,960	-	12,960	S
	II	38,880	-	38,880	S
Sep	I	10,368	-	10,368	S
	II	23,328	-	23,328	S
Oct	I	23,328	-	23,328	S
	II	53,136	-	53,136	S
Nov	I	53,136	-	53,136	S
	II	41,472	-	41,472	S
Total Cumulative Deficit				−290,359	7 Periods

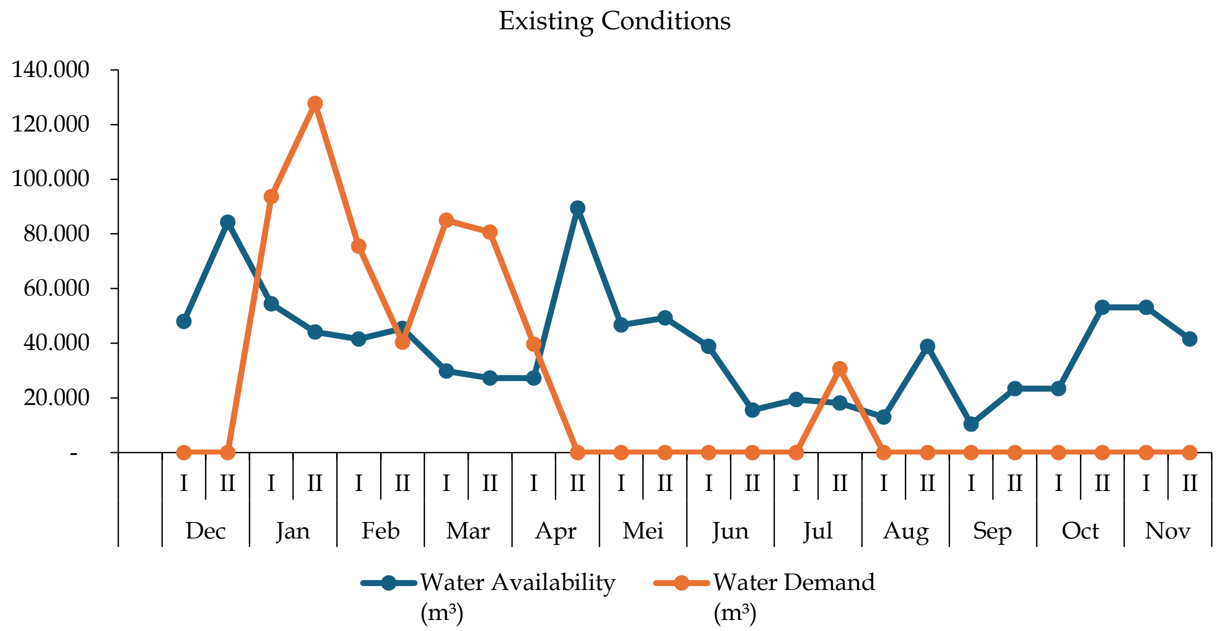

Figure 2. Water balance graph (water availability vs. water demand) — existing condition

The fluctuation pattern of water availability and demand throughout the year is shown in Figure 2. The water demand line (orange) spiked sharply in January II to 127,706 m^3, coinciding with the land preparation phase requiring a large volume of water for saturation and flooding, while the water availability line (blue) during the same period reached only 44,064 m^3, far below demand. The crossing pattern between the two lines in the December–January period and again in April–May underlies the cumulative deficit status in the Ripple method. After April, water demand dropped sharply toward zero as the rice planting season ended, while water availability continued to fluctuate following rainfall patterns, so all periods from May II through November had surplus status and can be used to refill the embung storage in the following season.

Water Balance and Deficit Analysis

The Ripple method (cumulative mass curve) was used to determine the Effective Storage Capacity (ESC) required for the water supply system to meet demand during deficit periods by utilizing surplus water from previous periods. Its working principle is to cumulatively accumulate inflow (water availability) and outflow (water demand) values per period (ΣInflow and ΣOutflow), then compare the difference (ΣOutflow − ΣInflow) to identify the maximum cumulative deficit. Surplus Status (S) occurs when ΣInflow > ΣOutflow (negative difference), while Deficit Status (D) occurs when ΣOutflow > ΣInflow (positive difference). Full analysis results are presented in Table 2. Based on Table 2, during December I through January II the system remained in surplus status (S) as cumulative water availability exceeded demand. Entering February I, status changed to deficit (D) with a difference of 24,754 m^3, progressively increasing to its highest value in April I of 140,647 m^3 — the cumulative deficit peak. After April I, the deficit began declining in April II (51,223 m^3) and May I (4,567 m^3), before returning to surplus from May II through year-end. Following the Ripple principle, ESC is set based on this maximum cumulative deficit value, namely.

Table 2. Summary of Ripple method analysis (cumulative water balance)

Month/Period	Inflow (m^3)	Outflow (m^3)	Cumulative difference (m^3)	Status
December I	47,952	0	-47,952	S
December II	84,240	0	-132,192	S
January I	54,432	93,675	-92,949	S
January II	44,064	127,706	-9,307	S
February I	41,472	75,533	24,754	D
February II	45,360	40,332	19,726	D
March I	29,808	84,910	74,828	D
March II	27,216	80,580	128,192	D
April I	27,216	39,671	140,647	D
April II	89,424	0	51,223	D
May I	46,656	0	4,567	D
May II	49,248	0	-44,681	S
June I	38,880	0	-83,561	S
June II	15,552	0	-99,113	S
July I	19,440	0	-118,553	S
July II	18,144	30,636	-106,060	S
August I	12,960	0	-119,020	S
August II	38,880	0	-157,900	S
September I	10,368	0	-168,268	S
September II	23,328	0	-191,596	S
October I	23,328	0	-214,924	S
October II	53,136	0	-268,060	S
November I	53,136	0	-321,196	S
November II	41,472	0	-362,668	S
Effective Storage Capacity (ESC)			140,647	

*Cumulative deficit peak = ESC. Source: Calculation Results, 2026

$ESC = 140{,}647\ m^3$

The ESC value of 140,647.00 m^3 indicates that to meet all irrigation water demands for the Rice–Secondary Crop cropping pattern throughout the year, a storage facility with a minimum effective capacity of 140,647.00 m^3 is required. This capacity is the volume of water that needs to be stored during the surplus period (primarily December–January) and then gradually released to cover water shortfalls during deficit periods (February–May), thereby achieving year-round water balance equilibrium. This ESC figure is smaller than the required storage volume (Va) presented later because Va additionally incorporates evaporation, seepage, and sediment losses on top of the ESC-based demand volume, rather than the two figures being in conflict. This finding aligns with Jonizar & Martini (2017), who also reported seasonal water deficits in rainfed paddy fields due to the absence of storage infrastructure, and is consistent with water balance assessments conducted in other Indonesian sub-watersheds facing similar dry-season shortfalls (Fitria et al., 2025). Due to complete dependence on rainfall without storage, the Cropping Index under existing conditions only reaches CI 100 (Murdiana & Fadli, 2016).

Sample Calculation of Effective Storage Capacity (ESC) – Ripple Method

The Effective Storage Capacity (ESC) is determined based on the peak value of the cumulative difference (ΣOutflow − ΣInflow) in the Ripple method. As an example, the calculation for the April I period (deficit peak):

ΣInflow April I = ΣInflow March II + Inflow April I
= 374,544 + 27,216 = 401,760 m^3

ΣOutflow April I = ΣOutflow March II + Outflow April I
= 502,736 + 39,671 = 542,407 m^3

Difference (D) = ΣOutflow − ΣInflow = 542,407 – 401,760 = 140,647 m^3 (5)

ESC = 140,647.00 m^3 (cumulative deficit peak)

Sample Calculation of Embung Storage Capacity (Va) – Kasiro Method

Embung storage capacity was calculated using the Kasiro (1997) equation: Va = Vu + Ve + Vi + Vs. The following is a sample calculation for land scenario A = 4.3 ha (selected scenario):

Water Demand Volume (Vu) = ESC = 140,647.00 m^3
Dry Season Evaporation Volume (Ve)
Akt = ½ × A = ½ × 4,3 = 2,150 ha
ekj = ETo × k × days = 27.91 mm/day × 0.70 × 15 = 293.07 mm/month

$$Ve = 10 \times Akt \times ekj = 10 \times 2.150 \times 293.07 = 6{,}301.01 \text{ m}^3 \quad (6)$$

(or: Ve = Ve/Akt × Akt = 2,930.71 × 2.150 = 6,301.01 m^3)
Water Seepage Volume (Vi)

$$Vi = 10\% \times Vu = 10\% \times 140{,}647.00 = 14{,}064.70 \text{ m}^3 \quad (7)$$

Sediment Storage Volume (Vs)

$$Vs = 10\% \times Vu = 10\% \times 140{,}647.00 = 14{,}064.70 \text{ m}^3 \quad (8)$$

Total Embung Capacity (Va)

$$Va = Vu + Ve + Vi + Vs \quad (9)$$

Va = 140,647.00 + 6,301.01 + 14,064.70 + 14,064.70
Va = 175,077.41 m^3

Sample Calculation of Embung Dimensions (Scenario A = 4.3 ha)

The physical dimensions of the embung were determined with a rectangular cross-section following the land shape from ArcGIS digitization, consistent with GIS-based site identification approaches used for rainwater-harvesting ponds elsewhere in Indonesia (Suni et al., 2023). The 4.3 ha embung site (approximately 5.6% of the 77 ha study area) is planned on a non-productive depression area rather than active paddy land, as shown in Figure 3. For the 4.3 ha land scenario:

Length × Width = 240 m × 180 m = 43,200 m^2
Storage depth T = 4.0 m (small embung standard, MoPW Circular No. 07/SE/M/2021)

$$\text{Volume Embung} = P \times L \times T = 43{,}200 \times 4.0 = 172{,}800.00 \text{ m}^3 \quad (10)$$

Check: Volume Embung < Va ⟹ 172,800.00 < 175,077.41 (deficit 2,277.41 m^3)

Embung alone is insufficient, requires additional Long Storage.

Sample Calculation of Long Storage Dimensions – Strickler Method

Long storage cross-section dimensions were calculated using the Strickler method. The design discharge was first determined:

$$Q_{des} = Ir \times A / 1{,}000 = 1.280 \times 77 / 1{,}000 = 0.0986 \text{ m}^3/\text{s} \quad (11)$$

For selected dimensions b = h = 1.0 m, Strickler coefficient K = 40 (equivalent to Manning n = 0.025, earthen channel), slope S = 0.0002:

Wetted Area: A = b × h = 1.0 × 1.0 = 1.0000 m^2
Wetted Perimeter: P = b + 2h = 1.0 + 2 × 1.0 = 3.0000 m
Hydraulic Radius: R = A/P = 1.0000/3.0000 = 0.3333 m

$$\text{Flow Velocity (Strickler): } V = K \times R^{2/3} \times S^{1/2} \quad (12)$$

$V = 40 \times (0.3333)^{2/3} \times (0.0002)^{1/2} = 0.2720$ m/s
Capacity Discharge:

$$Q_{cap} = A \times V = 1.0000 \times 0.2720 = 0.2720 \text{ m}^3/\text{s} \quad (13)$$

Check: $Q_{cap} \geq Q_{des} \Rightarrow 0.2720 \geq 0.0986$ m^3/s Satisfied. Note: this velocity (0.272 m/s) is below the 0.3–0.6 m/s minimum generally recommended for earthen channels to prevent sediment deposition, a failure mode also highlighted for small-scale irrigation storage structures elsewhere (Umukiza et al., 2023); given the 4,562 m length of the long storage, this indicates a sedimentation risk comparable to that identified in useful-life assessments of other small Indonesian reservoirs (Widyantara et al., 2026), addressed further in the Limitations below.

Total Depth: H = h + freeboard = 1.0 + 0.30 = 1.3 m
Long Storage Volume:

$$Volume\_LS = A \times L = 1.0000 \times 4{,}562 = 4{,}562.00 \text{ m}^3 \quad (14)$$

Total Volume = Embung Volume + Long Storage Volume = 172,800.00 + 4,562.00 = 177,362.00 m^3 (101% of Va = 175,077.41 m^3)

Embung Dimension Planning

Embung land area was determined through 38 trial-and-error scenarios ranging from 4.7 ha to 1.0 ha. Selected scenarios representing this selection process are presented in Table 3. The embung was able to independently meet the storage requirement (Va) up to the 4.5 ha scenario, but from the 4.4 ha scenario onward the embung volume was no longer sufficient and required supplementation from long storage. In the 4.3 ha scenario, the combination of Embung Volume and Long Storage Volume yielded a Total Volume = 177,362.00 m³ or 101% of Va, making this the minimum land area that still satisfies the Total Volume ≥ Va requirement. Scenarios below 4.2 ha no longer met the requirement because the reduction in embung cross-section was far faster than the fixed contribution from long storage.

Table 3. Comparison of selected embung land area scenarios

Land (ha)	Va (m³)	Embung volume (m³)	Total volume (m³)	Ratio volume/Va	Status/notes
4.70	175,663.56	190,000.00	194,562.00	111%	Meets
4.60	175,517.03	185,000.00	189,562.00	108%	Meets
4.50	175,370.49	181,300.00	185,862.00	106%	Meets (Standalone)
4.40	175,223.96	172,800.00	177,362.00	101%	Meets
4.30	175,077.41	172,800.00	177,362.00	101%	Meets (Selected)
4.20	174,930.89	164,500.00	169,062.00	97%	Does Not Meet
4.00	174,637.82	161,000.00	165,562.00	95%	Does Not Meet
3.80	174,344.74	153,000.00	157,562.00	90%	Does Not Meet
3.20	173,465.53	127,100.00	131,662.00	76%	Does Not Meet (≈75%)
2.50	172,439.78	99,900.00	104,462.00	61%	Does Not Meet
2.10	171,853.64	82,500.00	87,062.00	51%	Does Not Meet (≈50%)
1.50	170,974.43	58,800.00	63,362.00	37%	Does Not Meet
1.00	170,241.75	39,100.00	43,662.00	26%	Does Not Meet

Combination of Embung and Long Storage as the Selected Technical Solution

To cover the water deficit during critical periods, two complementary technical solution alternatives were formulated: an embung as the primary storage and long storage as supplementary storage while also serving as a distribution channel. The embung was planned on the selected 4.3 ha land area with a cross-sectional dimension of L × W = 240 × 180 m and storage depth T = 4.0 m, yielding a storage Embung Volume = 172,800.00 m³. The embung is located at an elevation of ±39.46 m, higher than the paddy field elevation (±25 m), enabling gravity-fed water distribution without a pumping system. This approach is consistent with scaling-up practices for rainfed embungs reported by Sudianto et al. (2024). As a complement, the long storage was planned with a square cross-section with base width and water depth b = h = 1.0 m, total depth (including 0.30 m freeboard) H = 1.3 m, and a total length following the land contour of L = 4,562 m. Its volume was computed as static storage (area × length), with the Strickler method (coefficient K = 40, bed slope S = 0.0002) applied only as a supplementary conveyance check. The long storage is laid out along the contour at the upper edge of the field perimeter, above the adjacent tertiary channels, so that its distribution to the paddy fields is likewise gravity-based; this layout assumption should be confirmed by detailed topographic survey at the design stage. These dimensions yield a channel capacity discharge of Q_cap = 0.272 m³/s, which satisfies the design discharge of Q_des = 0.0986 m³/s, and contributes an additional storage volume of 4,562.00 m³. The combination of these two hydraulic structures produces a total system storage volume of V_Total = 177,362.00 m³, equivalent to 101% of the required storage volume of Va = 175,077.41 m³ (surplus of 2,284.58 m³), covering all water deficits during the critical period, as summarized in Table 4.

Figure 3 shows the layout of the embung and long storage from map digitization using ArcGIS based on Indonesia Topographic Map (RBI) data at a scale of 1:6,000. The embung (green-marked area in the legend) is positioned in a depression on non-productive land in the northern part of the site, where it collects effective rainfall and surface runoff from the local sub-catchment area (DTA) rather than from a perennial river, consistent with the rainfed character of the site, while the long storage (orange line) encircles the outer boundary of the 77 ha paddy field area along 4,562 m, collecting rainfall runoff from the sub-catchment while also functioning as a secondary distribution channel leading to tertiary channels (yellow lines) dividing the paddy plots. Positioning the embung at a higher elevation than the paddy fields enables entirely gravity-fed water distribution without requiring pumps, thereby reducing long-term operating costs, supporting embung governance and management outcomes reported for other rainfed sites (Wadu et al., 2023).

Table 4. Summary of embung and long storage dimensions and storage volumes

Parameter	Embung	Long storage
Main Dimensions	240 × 180 m	b = h = 1.0 m
Depth/Height	T = 4.0 m	H = 1.3 m
Length	-	L = 4,562 m
Storage Volume	172,800.00 m³	4,562.00 m³
Cost Estimate	IDR 14.20 billion	IDR 1.50 billion

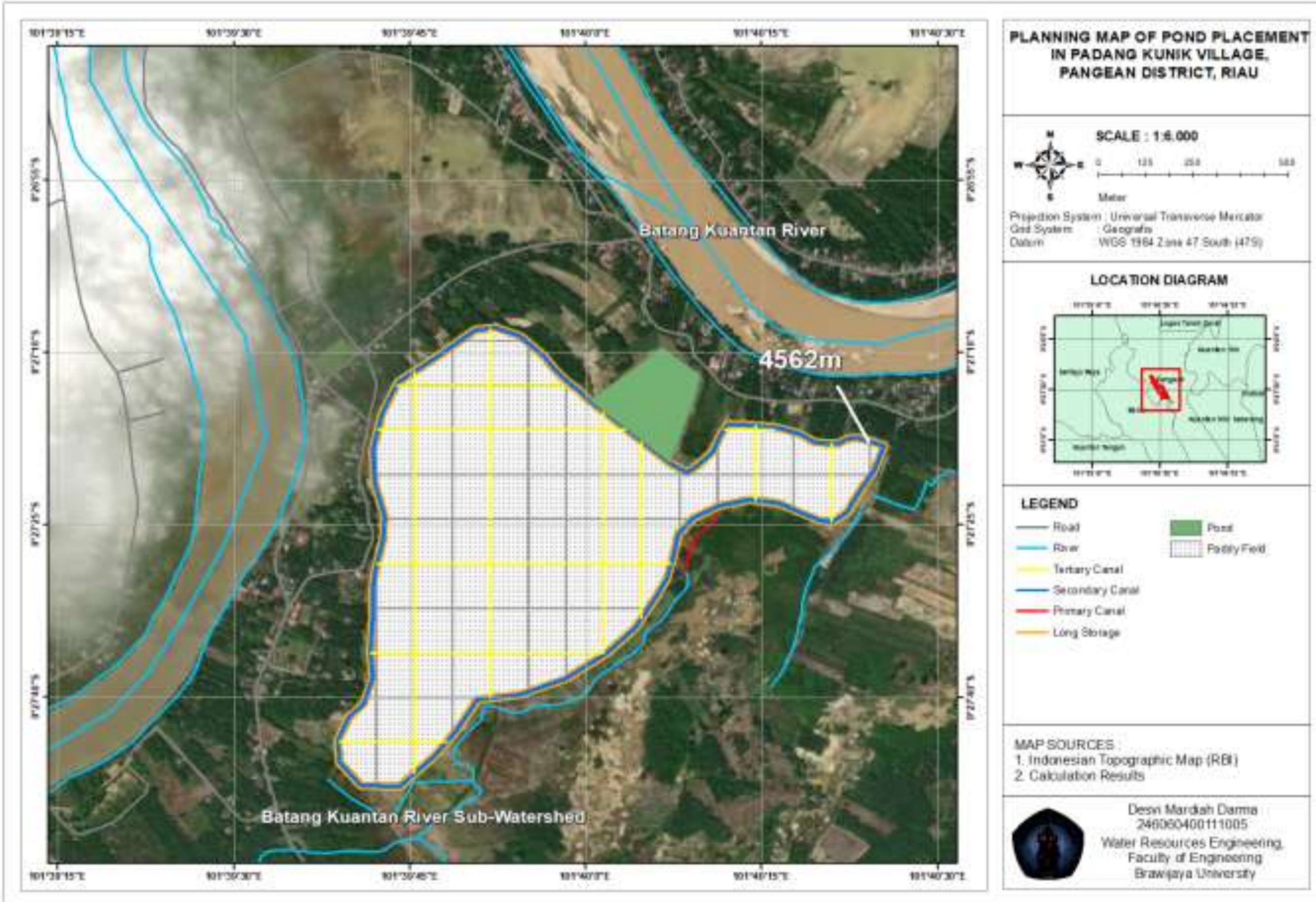

Figure 3. Planned location map of embung and long storage in Padang Kunik Village

Discussion of Total Volume/Va Ratio Scenarios: 100, 75, and 50%

Of the 38 trial-and-error scenarios (Table 3), three points were used as benchmarks for storage requirement fulfillment, namely scenarios where the Total Volume/Va ratio approached 100, 75, and 50%. These three scenarios occurred at land areas of 4.3 ha (ratio 101%), 3.2 ha (ratio 76%), and 2.1 ha (ratio 51%), as summarized in Table 5 below.

Table 5. Comparison of scenarios at total volume/Va ratio

Scenario	Land (ha)	Va (m^3)	Total volume (m^3)	Ratio (%)	Status
100%	4.3	175,077.41	177,362.00	101	Meets
75%	3.2	173,465.53	131,662.00	76	No
50%	2.1	171,853.64	87,062.00	51	No

Scenario 100% (Land 4.3 ha)

In this scenario, the combination of Embung Volume = 172,800.00 m^3 and Long Storage Volume = 4,562.00 m^3 yields a Total Volume = 177,362.00 m^3, or 101% of Va = 175,077.41 m^3 (surplus of 2,284.58 m^3). This means that the entire storage requirement during the deficit period (dry season) can be fully met by the embung and long storage system without the need for any additional water sources. This scenario represents the minimum critical threshold at which the combination of both hydraulic structures exactly meets the storage requirement, making it the basis for the embung land area recommendation in this study.

Scenario 75% (Land 3.2 ha)

At 3.2 ha, the Total Volume only reaches 131,662.00 m^3 or 76% of Va = 173,465.53 m^3, with a deficit of 41,803.53 m^3 (24% of the requirement). The embung and long storage system can only cover three-quarters of the dry season irrigation storage requirement. The remaining 24% must be met from other sources, such as direct rainfall during the planting period, replanning of the planting schedule, or deep wells and surface water pumps. This scenario may be considered as an emergency alternative if land acquisition of 4.3 ha cannot be achieved, but still requires a water deficit mitigation strategy.

Scenario 50% (Land 2.1 ha)

At 2.1 ha, the Total Volume only reaches 87,062.00 m³ or 51% of Va = 171,853.64 m³, with a large deficit of 84,791.64 m³ (49% of the requirement). The embung and long storage system can only meet half of the irrigation storage requirement, making the risk of crop failure due to water shortage very high if no significant alternative water source is available. Therefore, this scenario is not recommended unless accompanied by significant changes to the irrigation strategy, such as substituting part of the rice planting area with secondary crops with much lower water requirements, or adding raw water sources from outside the sub-watershed.

Economic Feasibility and Implications for Cropping Index Improvement

The construction cost estimates for the embung and long storage remain indicative in nature, based on a proportional scale relative to storage volume, and require further verification using the local Unit Price Work Analysis (AHSP), in line with storage-based water allocation studies that emphasize the importance of proportional preliminary cost estimation at the planning stage (Ariyanto, 2022), and with the economic feasibility approach used for other pump- and gravity-fed reservoir water-supply schemes in Indonesia (Lufira et al., 2025). The total combined investment estimate for both hydraulic structures amounts to approximately IDR 15.70 billion, dominated by the embung component, which accounts for approximately 90% of the total cost while also providing more than 97% of the system's storage volume. This confirms that the embung remains the primary component in terms of volumetric efficiency, while the long storage serves as a complement with a relatively higher unit cost per m³ but is nonetheless necessary to surpass the technical feasibility threshold (V Total ≥ Va) given the available land area; sound operation and community governance arrangements are also central to sustaining these benefits, as documented for other rainfed embung systems (Wadu et al., 2023). With year-round water demand fully met, the Cropping Index has the potential to increase from CI 100 to CI 200, consistent with cropping-intensity optimization achieved through improved reservoir water management elsewhere in Indonesia (Agastya et al., 2026), with irrigation-system optimization that raised cropping intensity in other Indonesian irrigation areas (Maulana et al., 2025), and with the economic viability of on-farm storage sizing reported for rainfed rice systems (Panigrahi et al., 2005), as well as the central role of reliable irrigation in boosting paddy field rice production reported in other rainfed locations in Sumatra (Murdiana & Fadli, 2016), and complementary to on-farm water-saving irrigation practices such as intermittent irrigation and the Jajar Legowo cropping system recommended for other rainfed areas in Sumatra (Ramadhan et al., 2024) and to irrigation-scheduling optimization approaches applied elsewhere in Indonesia (Kharistanto et al., 2025).

This study has several limitations that warrant attention at the advanced planning stage. First, the determination of the embung location and long storage alignment was still based on spatial analysis using digital imagery/map data (ArcGIS) without detailed topographic surveys and direct field geotechnical investigations; therefore, the stability of the excavation walls, the bearing capacity of the embung's subgrade soil, and the assumed gravity-based layout of the long storage need to be confirmed through boring or sondir tests and topographic survey prior to construction. Second, the low design flow velocity of the long storage (0.272 m/s, below the 0.3–0.6 m/s threshold generally recommended to prevent sedimentation) indicates a sedimentation risk that could progressively reduce its effective storage volume over the structure's service life; periodic desilting, a steeper bed slope, or channel lining should be evaluated at the design stage, and post-construction performance should be monitored using structured assessment approaches such as those applied to other small storage structures (Sapay et al., 2026). Third, the cost estimates presented are proportionally scaled to storage volume and do not yet reference the detailed Unit Price Work Analysis (AHSP) of Kuantan Singingi Regency, meaning these figures require correction at the stage of preparing the Detailed Cost Estimate (Bill of Quantities). Fourth, this study only extends to the recommendation and pre-design stage and does not encompass the preparation of a Detail Engineering Design (DED) or an environmental impact assessment (AMDAL) for the recommended infrastructure, making both aspects a priority in subsequent research and technical planning stages.

Conclusion

The 77 ha of rainfed paddy fields in Padang Kunik Village experienced water deficits in seven separate periods, interrupted by a surplus in February II, namely January I, January II, February I, March I, March II, April I, and July II, with the cumulative deficit under the Ripple method peaking in April I at 140,647.00 m³, established as the Effective Storage Capacity (ESC). Due to complete dependence on rainfall without storage infrastructure, the Cropping Index under existing conditions only reached CI 100. The most effective technical solution to cover the deficit is a combination of an embung on 4.3 ha (L × W = 240 × 180 m, T = 4.0 m, Embung Volume = 172,800.00 m^3) with long storage of square cross-section (b = h = 1.0 m, H = 1.3 m, L = 4,562 m, K = 40), yielding a Total Volume = 177,362.00 m^3 or 101% of required storage Va = 175,077.41 m^3. Water distribution from the embung to the paddy fields can be carried out by gravity since the embung elevation (±39.46 m) is above the paddy field elevation (±25 m); the long storage, laid out along the contour above the tertiary channels, is likewise designed for gravity distribution, subject to confirmation by detailed topographic survey. With water requirements met throughout the year, the Cropping Index has the potential to increase from CI 100 to CI 200. Further research is recommended to prepare detailed topographic surveys, geotechnical investigations, a Detailed Engineering Design (DED), and a Detailed Cost Estimate (Bill of Quantities) prior to the realization of embung and long storage construction.

Acknowledgements
The authors express gratitude to the Department of Water Resources Engineering, Faculty of Engineering, Universitas Brawijaya, for academic support during this research, and to the Sumatera III River Basin Organization (RBO) of the Riau Region for providing the necessary hydrological data.

Author Contributions
Conceptualization, D.M.D. and S.W.; methodology, investigation, original draft preparation, D.D.; formal analysis, D.D. and T.B.P.; manuscript editing and review, supervision, S.W. and T.B.P. All authors have read and agreed to the published final manuscript.

Funding
This research received no external funding.

Conflicts of Interest
The authors declare no conflicts of interest in this research.

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