

WATER BALANCE CHARACTERISTICS OF KEI KECIL ISLAND, SOUTHEAST MALUKU: AN INITIAL APPROACH TO GROUNDWATER MANAGEMENT ON A SMALL CARBONATE ISLAND

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ABSTRACT

The hydrogeological system of small carbonate islands is unique and complex. However, water resource needs on small islands rely heavily on freshwater available as a lens within the island. The volume of water in this freshwater lens depends significantly on the fluctuations of water supply to the island system. A water balance analysis was conducted to determine temporal and spatial rainfall and evapotranspiration levels from 2000 to 2025, using monthly averages for each year. Based on these parameters, the intensity of water input to the island was considered to construct a groundwater flow system model. The fracture system indicates that Kei Kecil Island undergoes natural recharge during precipitation events. The water balance results reveal a characteristically high rate of water input into the island system, influenced by high rainfall intensity and evapotranspiration rates that cause water loss. A surplus (positive value) indicates that water resource availability is maintained—specifically from January to June—even though the volume of water entering the system declines between April and June. Groundwater management becomes critical during deficit (negative) conditions, which occur from July to November. Given the relatively low water storage capacity—ranging from approximately 4.95 to 63.75 mm—comprehensive groundwater management is essential to effectively maintain the flow system and ensure adequate storage within the freshwater lens..

Keywords: water balance, groundwater, small carbonate island, Kei Kecil Island

INTRODUCTION

Small islands have limited freshwater resources because of their small land area and limited recharge zones, and their groundwater systems interact directly with the marine environment (Imig et al., 2025). Consequently, groundwater availability on small islands depends heavily on the balance between precipitation input and water loss (Panthi et al., 2024) through evapotranspiration, surface runoff, groundwater discharge into the sea, and human extraction (Bailey et al., 2014). On inhabited small islands, limited information on hydrogeology and hydrological characteristics can hinder assessment of water resource capacity and the

development of management strategies (Chui & Terry, 2013). Understanding the characteristics of the groundwater balance is highly beneficial for understanding water availability and groundwater sustainability in small island systems

Carbonate islands exhibit distinct hydrogeological characteristics, particularly regarding the aquifer systems found within their relatively homogeneous and extensive rock formations. Porosity and permeability in carbonate rocks are governed by fracture networks, dissolution cavities, primary porosity, and karst development, resulting in heterogeneous patterns of infiltration and

groundwater recharge distribution. The hydrological cycle on small islands is relatively short; rainfall serves as the primary source of groundwater recharge, followed by surface runoff and subsequent processes involving either precipitation or groundwater discharge into the sea. Variations in recharge volume and distribution play a critical role in the formation and persistence of freshwater lenses on small carbonate islands. Thus, analysing the balance between precipitation and evapotranspiration provides preliminary insights into the water-availability conditions that may sustain the groundwater system.

The relationship between water balance and groundwater resources is increasingly significant because freshwater lenses on small islands are dynamic and respond to changes in water input and loss (Ley et al., 2023). Recharge derived from precipitation infiltration is a key mechanism governing the development and evolution of freshwater lenses, whereas evapotranspiration reduces the volume of water available to reach the saturated zone (Rusli et al., 2021). Furthermore, topography, soil type, land cover, evapotranspiration, and the island's geological characteristics can influence the magnitude and spatial distribution of recharge (Rossi et al., 2022). These conditions indicate that water-balance information is not only crucial for understanding surface hydrological conditions but also serves as a preliminary approach to evaluating the potential water availability supporting the groundwater system on carbonate islands (Yao et al., 2019).

Kei Kecil Island in Southeast Maluku Regency is one of the carbonate islands in Eastern Indonesia that relies heavily on groundwater resources. Previous research on Kei Kecil Island indicates that the study area is dominated by carbonate rocks—including reef limestone and Quaternary carbonate deposits—with hydrogeological characteristics shaped by porosity, fracturing, and carbonate dissolution. Measurements from five observation wells show groundwater level elevations ranging from −0.4 to 6.7 m relative to Mean Sea Level. Based on the Ghyben–Herzberg approach (Sun et al., 2023), the theoretical thickness of the freshwater lens at four locations with positive groundwater levels ranges from 64 to 268 m. These results demonstrate the existence of a significant groundwater system on Kei Kecil

Island; however, previous studies focused primarily on groundwater-level characteristics and the estimated theoretical thickness of the freshwater lens, whereas water-balance characteristics—a fundamental factor in the recharge process—have not yet been quantitatively analysed (Cellone et al., 2018).

Based on the research gap identified above, research is needed to integrate the rainfall characteristics with evapotranspiration to provide an overview of the water balance system on Kei Kecil Island. This research can identify input and output processes to develop the island's hydrogeological system. For a small island with a carbonate system, water balance analysis provides preliminary information and identification of the groundwater system, especially for fractured media.

This research aims to characterise for the rainfall and evapotranspiration characteristic to develop the hydrogeological system of Kei Kecil Island. It can identify the island's water balance system using temporal and spatial methods, then evaluate the water balance system as a preliminary method to assess the sustainable groundwater availability and management.

RESEARCH METHOD

Study Area

The study was conducted on Kei Kecil Island, Southeast Maluku Regency, Maluku Province (Figure 1) a small island dominated by carbonate rocks, specifically reef limestone from Kai Kecil Formation (Light blue area) and Quaternary carbonate deposits from Ohoinoi and Weryahan Formation.

Given these geological conditions, the groundwater flow system exhibits both primary and secondary porosity, closely linked to fracturing and dissolution processes within the lithology. Previous hydrogeological research indicates that the groundwater table ranges from −0.4 to 6.7 meters above mean sea level. Consequently, the study area's hydrogeological conditions present significant challenges; beyond the island's marine setting (Spellman et al., 2021), the presence of a freshwater lens must also be considered to obtain a comprehensive picture of groundwater resources on Kei Kecil Island.

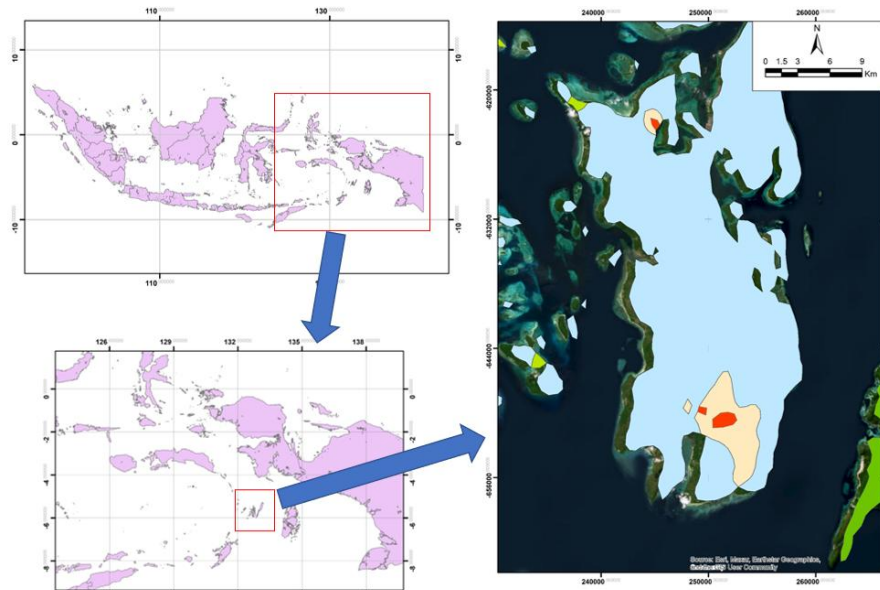


Figure 1. Map Index and Regional Geology Map of Kei Kecil Island

Data and Data Processing

This study used long-term precipitation, evapotranspiration, and available water capacity (AWC) data to characterise Kei Kecil Island's water balance. Precipitation and evapotranspiration data covered 2000 to 2025, while AWC data represented the upper 0–30 cm soil layer (Post et al., 2018).

Precipitation represents the principal water input to the island, whereas evapotranspiration represents the major atmospheric water loss (Zeitfogel et al., 2025). The AWC data were used as supporting information to describe the capacity of the upper soil layer to retain available water.

The datasets were processed spatially and temporally to obtain monthly and annual values within the Kei Kecil Island boundary. Spatial processing involved clipping the datasets to the study area, while temporal processing involved aggregating the datasets into monthly and annual periods. The resulting datasets were subsequently used to evaluate the temporal and spatial characteristics of water availability (Spellman et al., 2026).

Water Balance Analysis

The water balance was calculated based on the standard soil water bookkeeping procedure using Thornthwaite and Mather method (1957) the following equation:

$$[WB = P - ET]$$

where (WB) is the water balance (mm), (P) is precipitation (mm), and (ET) is evapotranspiration (mm).

This method explicitly incorporates the moisture holding capacity of the shallow root zone or available water capacity (AWC). The monthly calculations follow sequential steps:

1. Net atmospheric Difference: for each month, the difference between precipitation (P_i) and potential evapotranspiration (PET_i) is determined.
2. Accumulated potential Water Loss (APWL): During dry months ($P_i < PET_i$), the potential cumulative loss is:

$$APWL_i = APWL_{i-1} + |P_i - PET_i|$$

3. Soil Moisture Storage (ST): Soil storage within the upper 0–30 cm profile decays exponentially during moisture deficits:

$$ST_i = AWC \times \exp\left(-\frac{APWL_i}{AWC}\right)$$

During wet months ($P_i \geq PET_i$), storage is replenished up to the maximum capacity ($ST_{\max} = AWC = 35.6 \text{ mm}$):

$$ST_i = \min(ST_{i-1} + (P_i - PET_i), AWC)$$

4. Change in Soil Storage ($\Delta ST_i = ST_i - ST_{i-1}$)

When $P_i \geq PET_i$, $AET_i = PET_i$, when $P_i < PET_i$, Actual evapotranspiration is limited by moisture availability: $AET_i = P_i + |\Delta ST_i|$

5. Deficit and Suplus

Water surplus occur only after soil moisture storage reaches field capacity ($ST_i = AWC$):

$$DEF_i = PET_i - AET_i$$

$$SUR_i = (P_i - PET_i) - \Delta ST_i$$

(for $P_i > PET_i$; otherwise 0)

A positive value of (WB) indicates that precipitation exceeds evapotranspiration and represents a positive water balance or water

surplus. Conversely, a negative value indicates that evapotranspiration exceeds precipitation, representing a water deficit (Bedekar et al., 2019).

The water balance was analysed at monthly and annual scales to identify temporal variations in water availability. Spatial analysis was also conducted to identify variations in water balance across Kei Kecil Island. The resulting water balance characteristics were then interpreted in relation to the island's carbonate geological setting and groundwater system (Schneider & Kruse, 2003).

The calculated water surplus was interpreted as an indicator of water availability that may contribute to infiltration and groundwater recharge (Sheng et al., 2020). However, the surplus was not treated as equivalent to groundwater recharge because the partitioning of excess water is also influenced by infiltration, runoff, soil-water storage, and groundwater discharge (Herrmann et al., 2015).

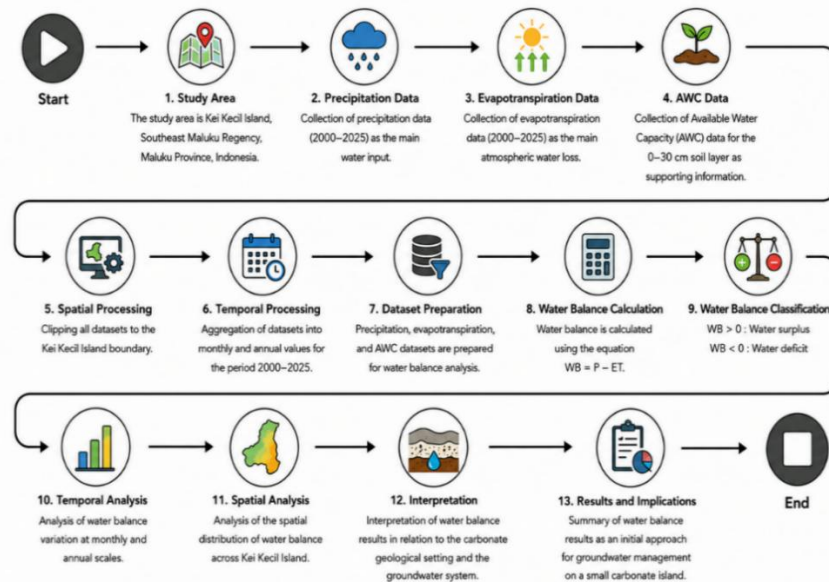


Figure 2. Research workflow for the water balance analysis of Kei Kecil Island, Southeast Maluku, Indonesia

RESULTS

Precipitation and Evapotranspiration Characteristics

Rainfall and evapotranspiration data for 2000–2025 show an annual rainfall intensity of 2,276.40 mm/year, while average annual evapotranspiration is 1,489.10 mm/year. This

shows that rainfall is the primary water input for Kei Kecil Island, while evapotranspiration is the dominant water loss in the island's system. The difference between rainfall and evapotranspiration indicates that groundwater input exceeds annual water loss, suggesting that the island's groundwater resources are substantial and stored as a freshwater lens. Figures 2 and 3 present the average monthly

rainfall and evapotranspiration values based on their temporal distribution.

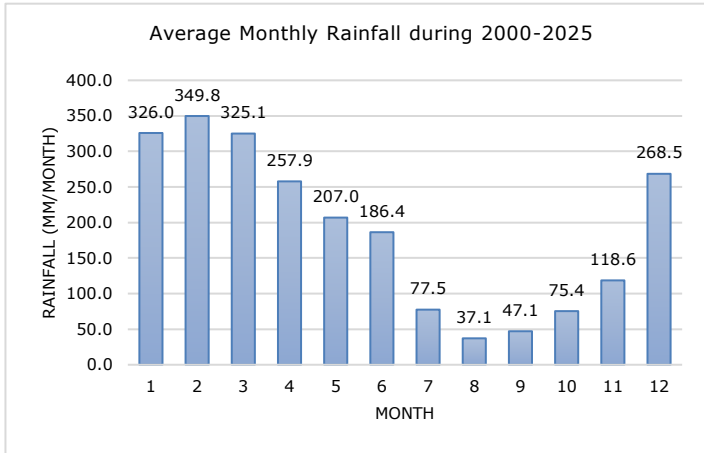


Figure 3. Monthly rainfall on Kei Kecil Island during 2000–2025.

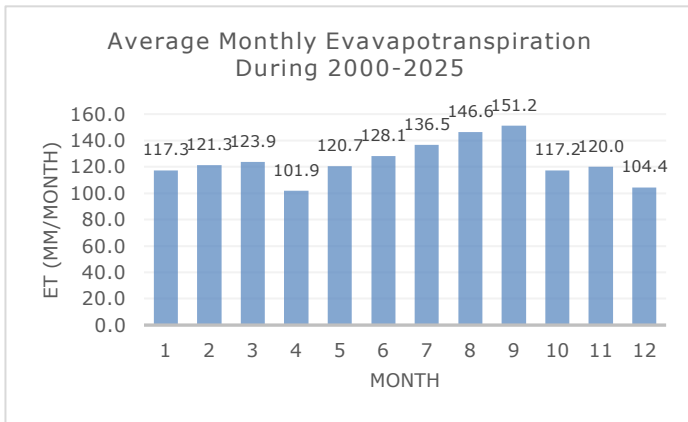


Figure 4. Monthly evapotranspiration on Kei Kecil Island during 2000–2025.

Available Water Capacity

A spatial analysis of available water capacity (AWC) was simulated for the 0–30 cm soil layer, revealing variations in water capacity across Kei Kecil Island (Figure 4). AWC values ranged from 4.95 to 63.75 mm, with a mean value of 35.60 mm. These values serve as baseline hydrogeological data for characterising groundwater conditions across the island.

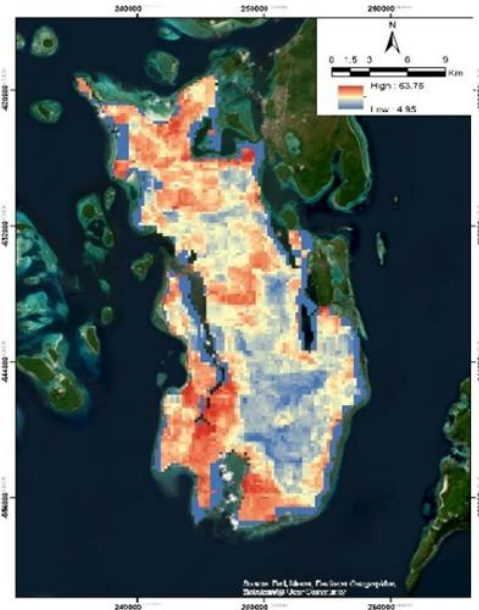


Figure 5. Spatial distribution of available water capacity (AWC) in the 0–30 cm soil layer on Kei Kecil Island

Table 1. Monthly water balance of Kei Kecil Island during 2000–2025.

Month	Rainfall (P)	PET	P–PET	APWL	Soil Moisture Storage (ST)	Change in Soil Moisture Storage (Δ ST)	Act ET	Mois-ture Deficit	Water Surplus
Jan	326	117.3	208.7	0	35.6	0	117.3	0	208.7
Feb	349.8	121.3	228.5	0	35.6	0	121.3	0	228.5
Mar	325.1	123.9	201.2	0	35.6	0	123.9	0	201.2
Apr	257.9	101.9	156	0	35.6	0	101.9	0	156
May	207	120.7	86.3	0	35.6	0	120.7	0	86.3
Jun	186.4	128.1	58.3	0	35.6	0	128.1	0	58.3
Jul	77.5	136.5	-59	59	6.79	-28.81	106.31	30.19	0

Month	Rainfall (P)	PET	P–PET	APWL	Soil Moisture Storage (ST)	Change in Soil Moisture Storage (Δ ST)	Act ET	Moisture Deficit	Water Surplus
Aug	37.1	146.6	-109.5	168.5	0.31	-6.47	43.57	103.03	0
Sep	47.1	151.2	-104.1	272.6	0.02	-0.3	47.4	103.8	0
Oct	75.4	117.2	-41.8	314.4	0.01	-0.01	75.41	41.79	0
Nov	118.6	120	-1.4	315.8	0	0	118.6	1.4	0
Dec	268.5	104.4	164.1	0	35.6	35.6	104.4	0	128.5
Total	2276.4	1489.1	787.3	—	—	0	1208.9	280.2	1067.5

Water Balance

The water balance values were calculated from simulated monthly average rainfall and evapotranspiration data (Tatas et al., 2015) for 2000–2025. Table 1 outlines the calculation using thornthwaite method, surplus period (December–June) with the total 1067,5 mm/year. The highest surplus occurred in February (228.5 mm), following the January (208.7 mm), March (201.2 mm), and April (156 mm). The surplus pattern shifting downward in May (86.3 mm) and June (58.30 mm) peaking with the deficit from July to November. Water deficit occur for 5 month with te total accumulation is 280.2 mm/year. Actual evapotranspiration value is 1208.9 mm/year has the lower than the value of precipitation due to limited soil as epikarst in dry season.

DISCUSSION

Water Balance Characteristics of Kei Kecil Island

The temporal distribution of water balance on Kei Kecil Island exhibits a pronounced seasonal dichotomy characterized by seven consecutive month of water surplus (December to June) and five consecutive months of moisture deficit (July to November). This patterns is intrinsically governed by the regional Australia-Asian monsoon circulation, the seasonal migration of the Inter-tropical Convergence Zone (ITCZ) and broad scale ocean atmosphere interaction in eastern Indonesia.

On Kei Kecil Island, the water balance value from December to June, the wet Northwest Monsoon delivers heavy convective rainfall (Peak value at 326–349.8 mm/month in January–March). This situation produces a substantial water surplus with the value 1067.5

mm/year, driving active gravitational percolation through epikarst fractures to replenish the freshwater lens.

July and November period, the dry Southeast Monsoon brings dry continental air from Australia, suppressing precipitation with P value < 78 mm/month and driving high evaporative demand wit PET up to 151.2 mm/month. This causes an extended moisture deficit value 280.2 mm and halts natural recharge or 0 value. El Nino dan positive Indian Ocean Dipole (IOD) event can prolong this dry phase and will affected to drought conditions and threatening the stability of the thin carbonate aquifer.

Groundwater System

Previous studies identified groundwater levels ranging from –0.4 to 6.7 m above sea level and estimated freshwater lens thicknesses of 64–268 m—using the Ghyben-Herzberg approach—at locations with positive groundwater levels. Simulated water balance results provide additional information regarding water resource availability on Kei Kecil Island. A positive water balance indicates downward groundwater percolation across varying Available Water Capacity (AWC) depths. This concept aligns with the freshwater lens principle on small islands, where recharge dominates subsurface water replenishment. In small island systems, groundwater recharge relies heavily on a positive water balance to allow water to pass through the unsaturated zone, reach the saturated zone, and merge with the freshwater stored in the aquifer.

Water Capacity

Available Water Capacity (AWC) has simulated at the shallow 0 – 30 cm profile and represents pedological setting of young carbonate island. Soils developed of reef limestone on Kei Kecil Island are the predominantly of thin, skeletal

soils (lithic leptosols). Low mean moisture storage capacity of only 35.60 mm and identified have limit retention buffering. During the dry season, shallow reservoir is completely exhausted within weeks, causing the moisture deficit. And then, upon the arrival of wet monsoonal precipitation in December, The rainwater immediately infiltrating directly via epikarst fractures, macropores, and dissolution conduits to the freshwater lens (Sharifazari et al., 2025). This rapid subsurface percolation is visually evidenced by the reef limestone outcrop (Figure 6), which displays well developed secondary porosity, dissolution cavities, and interconnected fracture networks that facilitate rapid transmission into the underlying carbonate aquifer.

CONCLUSION

Water balance analysis that has been simulated in 2000 - 2025 on Kei Kecil Island provides an overview of the condition of water input which is quite large, characterized by an average precipitation value reaching 2276.94 mm/year compared to the output that occurs on the island system, characterized by water loss due to the evapotranspiration process of 1489.10 mm/year. The positive period or surplus of water resources on the island occurs from January to March, but it decreases regularly starting from April to June. Negative conditions or deficits occur from July to November. The water storage capacity below the surface is identified as quite shallow, starting at a depth of 4.95 to 63.75 mm. This condition is in line with the fracture media which is spread on an island scale and makes Kei Kecil Island an active recharge that is direct and fast. Therefore, groundwater management strategies must be carried out on an island scale by maintaining the natural recharge system so that the freshwater lens on the island can also be well maintained.

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