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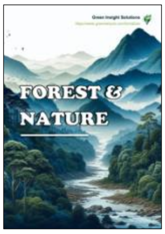

RESEARCH ARTICLE

# Modeling Groundwater Flow Dynamics Using the Master Recession Curve: Insights from Small Island Watersheds in Ambon, Indonesia

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## ABSTRACT

Understanding groundwater flow dynamics through the Master Recession Curve (MRC) is critical in evaluating groundwater behavior following periods of extraction or cessation of rainfall. This study employs the Depuit-Boussinesq model for aquifer flow storage, wherein recession coefficients and constants are primary determinants of the MRC's shape. This research aims to visualize the MRC using the Depuit-Boussinesq model to assess flow storage in small watershed areas within Ambon City, Maluku Province, Indonesia. The research methodology involved hydrological analysis across five watersheds, namely Wae Tomu, Wae Ruhu, Wae Batu Merah, and others, to model the relationship between recession constants, recession coefficients, and the MRC's shape. Data collection included groundwater head and aquifer parameters measurements over the study period. The visualization results reveal variations in MRC shapes among the watersheds. The Wae Tomu Watershed exhibits a steeper MRC, indicating a sharp decline in groundwater head. In contrast, the Wae Ruhu and Wae Batu Merah Watersheds display more gradual MRCs, reflecting slower and steadier head declines. The recession constant of the Wae Ruhu Watershed is higher, indicating a larger storage capacity, while the Wae Tomu Watershed has a lower recession constant, representing limited storage capacity. Furthermore, changes in the recession constantly affect the delay in head reduction, influencing the MRC's shape. This study underscores the significance of the relationship between recession coefficients, recession constants, and MRC shape in understanding groundwater flow dynamics. These findings provide valuable insights for more effective water resource management planning in small watershed areas.

## 1. Introduction

Understanding recession curves and aquifer behavior is important for water resource managers in predicting potential drought risks and effective water reserve mitigation strategies (Latuamury et al., 2020). Valuable information regarding storing and releasing aquifer water during periods of recession helps plan adequate water reserves (Basha, 2020; Stoelzle et al., 2013). The Master Recession Curve (MRC) model also helps evaluate aquifers' efficiency in storing and releasing water and determining the success of aquifer management (Latuamury et al., 2024b). Assessment of aquifer performance and MRC behavior is also important in planning and designing water management infrastructure such as wells, reservoirs, and water distribution systems (Chen et al., 2012; Heppner and Nimmo, 2005). Flow storage research using MRC from the Depuit-Boussinesq model is very important because it provides deep insight into the dynamics of groundwater flow, helps in planning and managing water resources, and provides important data to overcome drought challenges and ensure the sustainability of water management (Lee, 2014).

The Depuit-Boussinesq model is a mathematical model used to describe groundwater flow in porous aquifers. This model combines two approaches, namely the Depuit model, which assumes horizontal flow in the aquifer, and the Boussinesq model, which integrates the effects of head changes on vertical and horizontal flow (Latuamury et al., 2024b; Liang et al., 2017). The Depuit-Boussinesq model assumes that the aquifer is porous; namely, the aquifer is a homogeneous and isotropic porous medium (Lee, 2014). This model assumes horizontal groundwater flow in an aquifer that is not too deep; the aquifer has a constant or almost constant thickness. This model also ignores changes in the head that are too large so that the groundwater head can be assumed to be a linear function of horizontal distance (Goswami et al., 2010).

The Depuit-Boussinesq model has uses in groundwater resource planning and management, including estimating well discharge, flow in aquifers, and the impact of water extraction (Latuamury et al., 2024b). This model can simulate groundwater flow in aquifers, which requires understanding the distribution and changes in groundwater head. However, this model is unsuitable for aquifers with varying thicknesses (Latuamury and Talaohu, 2020). This model ignores the effects of vertical flow, so it is less suitable for situations where vertical flow is significant. Practical uses: The Depuit-Boussinesq model is often used in hydrogeological studies to design and manage aquifer systems, such as determining the location and capacity of wells, modeling the impacts of water extraction, and forecasting changes in groundwater resources (Asad-uz-Zaman and Rushton, 2006). Several hydrological studies using the Depuit-Boussinesq Model (Alvarado, 2015; Zhang, 2008) have analyzed groundwater flow in the lowlands in North China using the Depuit-Boussinesq numerical approach to understand the impact of groundwater extraction on water availability. The results showed significant changes in groundwater heads and flow patterns, along with variations in water extraction rates. (Wilson, 2010) used the Depuit-Boussinesq model to assess groundwater depletion in the Central Valley, California, which is an area of intensive water extraction for agriculture, and the results of his research identified critical areas where decreasing groundwater heads could affect water supplies for agriculture and recommendations for sustainable management (Lee et al., 2018).

Assessment of groundwater recharge and flow in the Atacama Desert region, Chile, using the Depuit-Boussinesq Model. The study results provide insight into groundwater management in arid areas and the impact of changes in recharge patterns (Alvarado, 2015; Nurhadi, 2021). Research simulated groundwater flow with data on agricultural land use and irrigation practices in the Midwest USA, and the results showed a significant impact of intensive irrigation on groundwater head and horizontal flow (Johnson, 2013; Johnson, 2015). Assessing flow storage capacity and flow dynamics in aquifers in Kansas using the Depuit-Boussinesq Model, and the study results provide estimates of flow storage capacity and understand the influence of changes in groundwater heads on flow and aquifer dynamics (Smith 2012, 2011). The research results assess flow storage capacity in confined aquifers in the Central Valley of California, and the results show that flow storage capacity can be influenced by the management of water extraction and recharge (Johnson, 2013).

The Depuit-Boussinesq model, frequently utilized to analyze aquifer flow storage, has proven effective in accurately estimating flow storage capacity and supporting groundwater management planning (Kobayashi et al., 2010). For instance, (Lee, 2014) demonstrated that this model accurately estimates storage coefficients and aquifer behavior, providing a solid foundation for groundwater resource management in various regions. Another (Gonzales et al., 2009) study applied the Depuit-Boussinesq model to assess flow storage capacity in aquifers within the semi-arid Atacama Desert. The findings revealed that arid climate conditions significantly influence flow storage capacity, emphasizing the importance of this model for water resource planning and management in semi-arid regions. Furthermore, (El-Kadi, 2019) extended the application of this model to coastal aquifers in the Nile Delta. The study provided critical insights into the flow storage capacity in coastal areas and the impacts of seawater extraction and intrusion on aquifers. However, applying the Depuit-Boussinesq model to small islands, such as Ambon City in Maluku Province, remains scarce. Small islands possess unique hydrological characteristics, including limited groundwater storage capacity and high vulnerability to climate change impacts, such as increased seawater intrusion and decreased rainfall. In this context, understanding MRC and aquifer behavior becomes essential to support sustainable water management and mitigate water scarcity risks (Latuamury et al., 2024b).

This study introduces a novel approach by visualizing the MRC using the Depuit-Boussinesq model to evaluate flow storage capacity in the watersheds of small islands in Ambon City. This approach provides a clearer understanding of groundwater flow dynamics and contributes to designing more effective water resource management strategies in resource-limited areas. Furthermore, the study highlights the importance of understanding the relationship between recession coefficients, recession constants, and MRC shapes in responding to environmental changes, thereby contributing directly to climate change mitigation efforts in small islands. This research advances scientific knowledge and offers practical solutions for water resource management in small island regions, particularly in Ambon City, Maluku Province, Indonesia.

## 2. Materials and Methods

### 2.1. *Study Area*

The research was conducted in five small island watersheds in Ambon City, Wae Batu Merah, Wae Ruhu, Wae Batu Gajah, Wae Batu Gantung, and Wae Tomu Watersheds. These five watersheds were chosen considering that the availability of the River Flow Measurement Station from the Ministry of Public Works of Maluku Province and the spatial dynamics of land changes in the riverbank area are rapid and have implications for the hydrological conditions of the watershed. The morphometric characteristics of the five watersheds are presented in **Table 1** and **Fig. 1**.

**Table 1.** Morphometric characteristic of watersheds in the current study

| Watershed name | SPAS coordinates | | Watershed length (km) | Watershed width (km) | Circumference (km) |
|---|---|---|---|---|---|
| | X | Y | | | |
| Wae Batu Merah | 409415.73 | 9592511.44 | 4,69 | 2,65 | 23,12 |
| Wae Ruhu | 410922.34 | 9594695.91 | 6,46 | 3,29 | 47,96 |
| Wae Batu Gajah | 408291.73 | 9591503.334 | 5,22 | 2,25 | 18,49 |
| Wae Batu Gantung | 408291.73 | 9591235.01 | 4,92 | 4,24 | 25,32 |
| Wae Tomu | 409111.96 | 9592214.09 | 5,10 | 1,55 | 12,90 |

**Fig. 1.** Image of the location of five Ambon City watersheds (Latuamury et al., 2021).

### 2.2. *Study Procedure*

This research uses hydrooffice 12.0 software utilizing features from RC 4.0 for MRC visualization using the Depuit-Boussinesq model and aims to characterize baseflow recession and water storage capacity (**Table 2**). The stages in MRC modeling are 1) determining the MRC parameters to be optimized, including a combination of recession coefficient, recession constant, initial discharge, and recession volume; 2) starting exploring the recession parameters and finding an initial solution that is close to optimal; 3) Determine optimization methods to improve existing solutions; 4) validate the MRC obtained from observation data to increase its accuracy and reliability. Evaluate model performance with the RMSE metric; 5) Carry out hybridization iterations until convergence is achieved and the MRC parameters are optimal.

**Table 2.** Recession functions used in RC 4.0

| Conceptual model | Recession function | Storage type |
|---|---|---|
| Depuit-Boussinesq aquifer storage (Boussinesq, 1904) | $Q = Q_0(1 + \alpha_3 t)^{-2}$ | Shallow unconfined aquifer, a special case of power-law reservoir for Dupuit-Boussinesq aquifer model |

Notes: Q= discharge, t= time since the beginning of the recession, Q0= discharge for t =0, τ, n, α, β, ∅ - parameters to be determined by calibration. Based on Gregor and Malík (2012).

The operational stages of MRC implementation include collecting river flow data from stations during the 2007–2014 period; Import and filtering debit data and performing data validation to ensure quality and consistency; identifying relevant recession periods for baseflow recession analysis; setting initial parameters for the genetic algorithm including population size, mutation rate, and number of generations; implementation of optimization methods to improve the process of finding optimal solutions; running the optimization process to find the optimal MRC parameters; Uses calibration features to fit models to observed data. Validate the resulting MRC with independent data to ensure model reliability and accuracy, using an optimized MRC model for further hydrological analysis and practical water resource management applications. MRC modeling offers advantages in accuracy and reliability. However, it also faces challenges in complexity and computing time requirements. This method can be a very effective tool for hydrological analysis and management with the right approach.

## 3. Results and Discussions

### *3.1. Estimating Model using Depuit-Boussinesq Aquifer Storage Model*

The estimation of the Depuit-Boussinesq aquifer storage model involves analyzing baseflow recession parameters, including initial recession discharge ($Q_0$), recession coefficient (α-3), recession constant (τ), and recession volume (Q-Cal), to characterize groundwater flow behavior in five watersheds in Ambon City. The results reveal variations in recession parameters across the watersheds. The Wae Batu Merah Watershed exhibits the highest average initial recession discharge (4.75 $m^3/s$) and the most significant recession volume (2.9621 $m^3$), indicating substantial flow storage capacity and stable flow behavior. The Wae Batu Gajah Watershed has a relatively high initial discharge (4.61 $m^3/s$) but a lower recession volume (2.3745 $m^3$), signifying moderate flow storage capacity. The Wae Ruhu Watershed shows the highest recession constant (0.9465) and the lowest recession coefficient (0.055), reflecting stable aquifer behavior with significant groundwater storage capacity (recession volume 2.7738 $m^3$). The Wae Batu Gantung Watershed records a lower initial discharge (3.73 $m^3/s$) and a smaller recession volume (2.0978 $m^3$), with a more rapid decline in groundwater head than other watersheds. The Wae Tomu Watershed presents the lowest initial discharge (3.99 $m^3/s$), the highest recession coefficient (0.079), the lowest recession constant (0.924), and the smallest recession volume (1.8855 $m^3$), indicating limited flow storage capacity with a steep decline in groundwater head., as presented in **Table 3**.

**Table 3.** Calculation results of baseflow recession parameters in the five research watersheds

| Watershed name | Initial discharge ($m^3/s$) | Recession coefficient | Recession constant | Recession volume ($m^3$) |
|---|---|---|---|---|
| | **Q0** | **α-3** | **τ** | **Q-Cal** |
| Wae Batu Merah | 4.75 | 0.058 | 0.9436 | 2.9621 |
| Wae Ruhu | 4.55 | 0.055 | 0.9465 | 2.7738 |
| Wae Batu Gajah | 4.61 | 0.064 | 0.938 | 2.3745 |
| Wae Batu Gantung | 3.73 | 0.077 | 0.9259 | 2.0978 |
| Wae Tomu | 3.99 | 0.079 | 0.924 | 1.8855 |

Note: Recession segment data using SPSS, 2007–2014.

The recession coefficient indicates the rate of decrease in groundwater head over time after water extraction stops or decreases. The recession coefficient indicates how quickly an aquifer can recover from a period of intensive extraction. This value is useful for planning groundwater management and recharge strategies. A high recession coefficient indicates groundwater heads decreased rapidly after extraction stopped. It indicates that the aquifer has less storage or a rapid response to changes in flow. In contrast, a low recession coefficient indicates a slower decline in the head. It indicates that the aquifer has a greater storage capacity or a slower response to change (Latuamury et al., 2024b). Recession constant (storage coefficient or Storage constant) measures how much water is stored in the aquifer per unit change in head. It is measured in volumetric units per unit area per unit change in head. A high recession constant indicates that the aquifer has a large storage capacity to store more water per unit change in head, and a low recession constant indicates a lower storage capacity and less ability to store water per unit change in head. The constant recession is important in understanding the capacity of aquifers to store and release water and in designing effective water management systems (Latuamury et al., 2022b).

Initial discharge or Initial flow rate refers to the existing water flow rate at the start of the simulation or before any change in extraction conditions (Biswal and Marani, 2014; Sugiyama et al., 1997). The initial measured recession discharge indicates how much water flows from the aquifer before a change in extraction or recharge conditions occurs. Initial discharge provides basic information about the natural flow of an aquifer and is used as a reference for analyzing the impact of changes in extraction or recharge on flow (Latuamury et al., 2022a). Volume reset (Recession volume) is the total amount of water released from the aquifer during a recession or lowering head (Esfandiari et al., 1997; Rhodes et al., 2017). The total value indicates the total volume of water withdrawn from the aquifer over a certain period. Recession volume helps assess the impact of extraction or head changes on the total volume of water in the aquifer. It is also useful for planning recharge or mitigation to maintain balance in the aquifer (Latuamury et al., 2024b).

Globally, the Depuit-Boussinesq model has been applied to understand groundwater flow dynamics in various regions: In semi-arid areas like the Atacama Desert (Gonzales et al., 2009), recession coefficients and constants reflect the significant influence of arid climates on groundwater storage. The Wae Tomu Watershed, with its low recession constant, exhibits behavior similar to aquifers in such semi-arid areas. In coastal regions like the Nile Delta (El-Kadi, 2019), the model has been employed to assess the impacts of seawater extraction and intrusion on groundwater flow. The Wae Ruhu and Wae Batu Merah Watersheds, characterized by high recession constants and substantial storage capacities, demonstrate behaviors akin to coastal aquifers. The variation in recession parameters among the watersheds highlights differences in storage capacity and groundwater flow dynamics influenced by local geographical and hydrological conditions. Watersheds with high recession constants, such as Wae Ruhu, possess better storage capacities, which is crucial for sustainable groundwater management in small islands like Ambon City. This study provides critical insights for more effective water resource planning in regions vulnerable to climate change and seawater intrusion.

### *3.1.1. MRC using Depuit-Boussinesq aquifer storage model for the Wae Batu Merah Watershed*

The results of the recession parameter estimation for the Wae Batu Merah Watershed reveal significant variation in groundwater flow dynamics and storage capacity compared to the other watersheds studied. The initial recession discharge ($Q_0$) for Wae Batu Merah was 4.79 m³/s, the highest among the five watersheds. This suggests that it has a larger volume of water flowing from its aquifer before changes in extraction conditions, such as rainfall cessation, occur. The recession coefficient ($\alpha$-3) was recorded at 0.033, and the recession constant ($\tau$) was found to be 0.9675, with a flow volume (Q-Cal) of 3.0847 m³/s. These parameters indicate a relatively stable aquifer system that responds moderately to changes in groundwater extraction. Notably, the lower recession coefficient of Wae Batu Merah compared to Wae Tomu and Wae Batu Gantung suggests that the groundwater head in Wae Batu Merah declines more gradually. This indicates that the aquifer in Wae Batu Merah retains groundwater for a longer period and responds more slowly to changes in extraction or precipitation, as evidenced by a flatter MRC curve. These findings align with previous studies, such as those by (Gonzales et al., 2009), which associate higher recession coefficients with more rapid declines in groundwater levels, indicating more dynamic aquifer systems, as presented in **Fig. 2**.

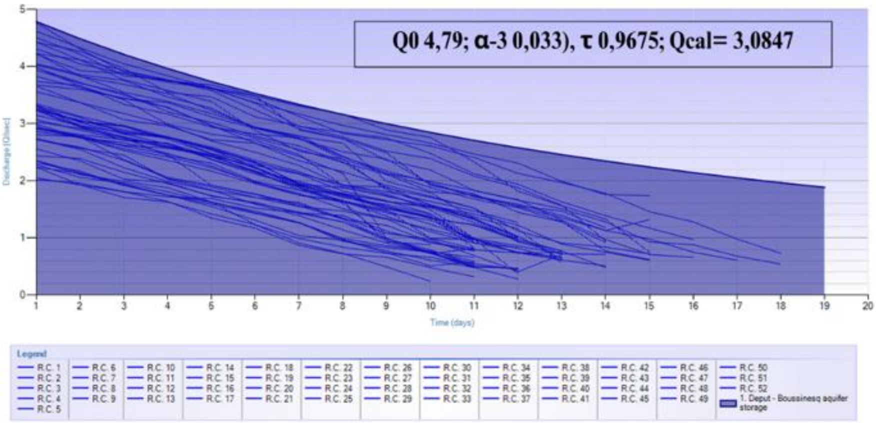

**Fig. 2.** MRC using the Depuit-Boussinesq aquifer storage model for the Wae Batu Merah Watershed.

The higher recession constant and flow volume in the Wae Batu Merah Watershed suggest a larger storage capacity than the Wae Batu Gajah, Wae Batu Gantung, and Wae Tomu Watersheds. A higher recession constant reflects a greater ability to store water per unit change in groundwater head, enabling Wae Batu Merah to absorb and retain a larger volume of groundwater. This is particularly valuable in regions with variable precipitation patterns, where groundwater is a crucial resource. Although the Wae Batu Merah Watershed has a higher storage capacity, its recession constant and volume are lower than those of the Wae Ruhu Watershed, which has a more efficient water retention system. This contrast suggests that the Wae Ruhu aquifer responds more quickly to changes in groundwater levels and is better suited for managing fluctuations in extraction or precipitation. These findings underscore the importance of considering local aquifer dynamics when designing sustainable groundwater management strategies.

The study's results significantly impact groundwater management in Ambon City and other small island regions. The moderate recession response of the Wae Batu Merah Watershed makes it a stable water source under typical usage conditions. However, understanding its slower recession dynamics is crucial for preventing over-extraction and ensuring sustainable water management as pressures on groundwater increase. This slower decline in groundwater levels provides an opportunity for more flexible management strategies, such as storing water for longer periods and reducing the risk of drought during dry seasons. The study also offers valuable context by comparing the Wae Batu Merah Watershed with regions like the Atacama Desert (Gonzales et al., 2009) and the Nile Delta (El-Kadi, 2019). In water-scarce areas, similar groundwater management models have helped optimize extraction systems and prevent issues like seawater intrusion, demonstrating the broader relevance of the findings. The results of this study, based on the Depuit-Boussinesq aquifer storage model, provide important insights into the groundwater flow and storage behavior in Ambon City. While the Wae Batu Merah watershed offers a stable water supply, its ability to retain water over extended periods is less than that of other watersheds, such as Wae Ruhu. These findings are critical for developing tailored groundwater management strategies that account for local variations in aquifer behavior and recession dynamics (Latuamury et al., 2024b).

### *3.1.2. MRC using Depuit-Boussinesq aquifer storage model for Wae Ruhu Watershed*

The estimation results for the Wae Ruhu Watershed show variation in the dynamics of groundwater flow and storage capacity compared to other watersheds. The initial recession discharge ($Q_0$) is recorded at 4.59 m³/second, which is lower than the Wae Batu Merah Watershed and Wae Batu Gajah Watershed but higher than the Wae Batu Gantung and Wae Tomu watersheds. The recession coefficient (α-3) for the Wae Ruhu watershed is 0.0151, indicating a slower decline in groundwater head. In contrast, the recession constant ($\tau = 0.9850$) is higher, reflecting a more stable aquifer response and greater storage capacity. The lower recession coefficient in the Wae Ruhu Watershed suggests that the decline in groundwater head in this area occurs more slowly compared to other watersheds with higher recession coefficients, such as Wae Batu Merah and Wae Batu Gajah. This indicates that the aquifer in Wae Ruhu is better at retaining groundwater for a more extended period and remains more stable, leading to a gentler MRC curve, which aligns with findings from previous studies by Gonzales et al. (2009) and El-Kadi (2019), as presented in **Fig. 3**.

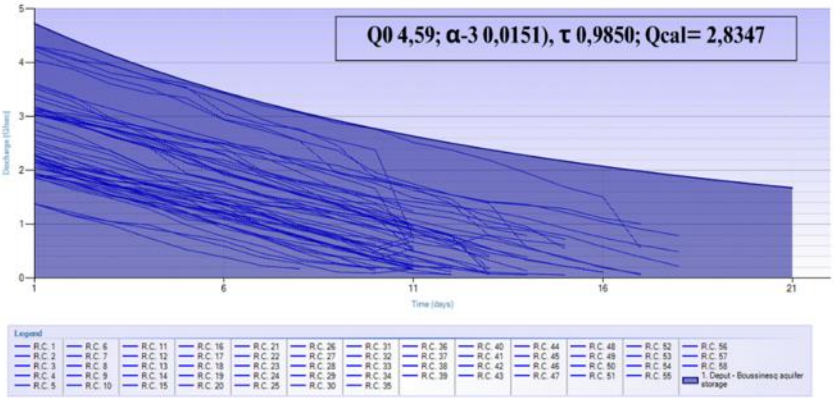

**Fig. 3.** MRC using the Depuit-Boussinesq aquifer storage model for the Wae Ruhu Watershed.

The recession constant (τ = 0.9850) and flow volume (Q-Cal = 2.8347 m³/second) in the Wae Ruhu Watershed indicate a larger storage capacity than others. The higher recession constant demonstrates the aquifer's ability to store more water per unit change in groundwater head, meaning the Wae Ruhu Watershed can absorb and retain more substantial water. The Wae Ruhu Watershed exhibits a lower recession coefficient and higher storage capacity than the Wae Batu Merah, Wae Batu Gajah, and Wae Batu Gantung Watersheds. This makes the Wae Ruhu aquifer more stable in responding to changes in groundwater flow. Similar studies in the Atacama and Nile Delta regions indicate that aquifers with low recession coefficients tend to be more stable and possess greater storage capacity, which is highly relevant for groundwater management in areas with over-extraction.

This research suggests that the Wae Ruhu Watershed, with its slower recession response and larger storage capacity, has the potential to become a more stable and reliable source of groundwater. Understanding the parameters of slower recession is crucial for designing sustainable groundwater management strategies, particularly in areas dependent on groundwater as a primary water supply. With a lower recession coefficient and greater storage capacity, the Wae Ruhu Watershed shows potential as a more stable and sustainable groundwater resource. Despite having a lower initial recession discharge than the Wae Batu Merah Watershed, the higher storage capacity in Wae Ruhu makes it more efficient at maintaining groundwater. This study provides important insights for managing water resources in regions with limited availability (Latuamury et al., 2024b).

### *3.1.3. MRC using Depuit-Boussinesq aquifer storage model for the Wae Batu Gajah Watershed*

The results of the recession parameter estimation for the Wae Batu Gajah Watershed indicate differences in the dynamics of groundwater flow and aquifer storage capacity compared to other watersheds studied. The initial recession discharge ($Q_0$) was recorded at 4.65 m³/s, higher than that of the Wae Batu Gantung and Wae Tomu Watersheds but slightly lower than that of the Wae Batu Merah watershed. This suggests that the Wae Batu Gajah Watershed has more water flowing from its aquifer than other watersheds. The recession coefficient for the Wae Batu Gajah Watershed was recorded at 0.035, which is higher than that of the Wae Batu Merah and Wae Ruhu Watersheds. This indicates that the decline in groundwater head in this watershed occurs more rapidly, with a steeper MRC curve, reflecting a quicker aquifer response to changes in extraction or the cessation of rainfall. These findings are consistent with previous studies, which indicate that aquifers with higher recession coefficients tend to respond faster to changes but with lower storage capacities. The recession constant (τ = 0.9656) and flow volume (Q-Cal = 2.5476 m³/s) for the Wae Batu Gajah Watershed suggest a larger storage capacity compared to the Wae Batu Gantung and Wae Tomu Watersheds, but smaller than that of the Wae Batu Merah and Wae Ruhu Watersheds. This indicates that the aquifer in the Wae Batu Gajah Watershed has a moderate storage capacity but responds more quickly to changes in extraction or rainfall conditions, as presented in **Fig. 4**.

The Wae Batu Gajah Watershed exhibits a faster aquifer response to changes in groundwater flow compared to the Wae Batu Merah and Wae Ruhu Watersheds. While it has a lower storage capacity, this aquifer can store more water than the Wae Batu Gantung and Wae Tomu Watersheds. Still, it is less effective in maintaining a long-term water supply if extraction increases. These findings are particularly relevant for regions prone to drought or those reliant on aquifers for water supply. This study shows that the Wae Batu Gajah Watershed, with its moderate storage capacity and quick response, has the potential to sustain water supply in the short term. However, with increased extraction, long-term groundwater supply challenges will arise. Understanding the rate of decline in groundwater heads is essential for designing sustainable groundwater management policies to avoid over-extraction, which could reduce water availability during dry seasons (Latuamury et al., 2024a). The study concludes that the aquifer in the Wae Batu Gajah Watershed has a moderate storage capacity and responds quickly to changes in extraction and rainfall conditions. Although it has a lower storage capacity than the Wae Batu Merah and Wae Ruhu Watersheds, these findings provide valuable insights for sustainable groundwater management in Ambon City, considering the local aquifer characteristics (Latuamury et al., 2024b).

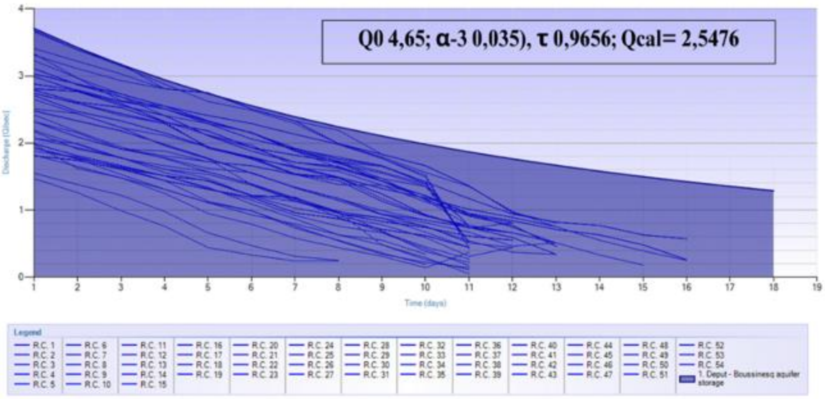

**Fig. 4.** MRC using Depuit-Boussinesq aquifer storage model for the Wae Batu Gajah Watershed.

### 3.1.4. MRC using Depuit-Boussinesq aquifer storage model for the Wae Batu Gantung Watershed

The recession constant and flow volume are crucial for assessing aquifer storage capacity. In the Wae Batu Gantung Watershed, the recession constant ($\tau = 0.9598$) and flow volume (Q-Cal = 2.2050 $m^3/s$) suggest that this aquifer has a higher storage capacity compared to Wae Tomu but lower than Wae Batu Merah, Wae Batu Gajah, and Wae Ruhu. The higher recession volume in Wae Batu Gantung compared to Wae Tomu suggests that its aquifer can store more water per unit of groundwater head change. However, the lower recession constant compared to other watersheds indicates that this aquifer has a lower storage capacity, and water will exit more quickly after changes in extraction or rainfall conditions. This suggests that, although the Wae Batu Gantung aquifer stores more water than the Wae Tomu aquifer, it responds more quickly to fluctuations in flow or weather changes, as presented in **Fig. 5**.

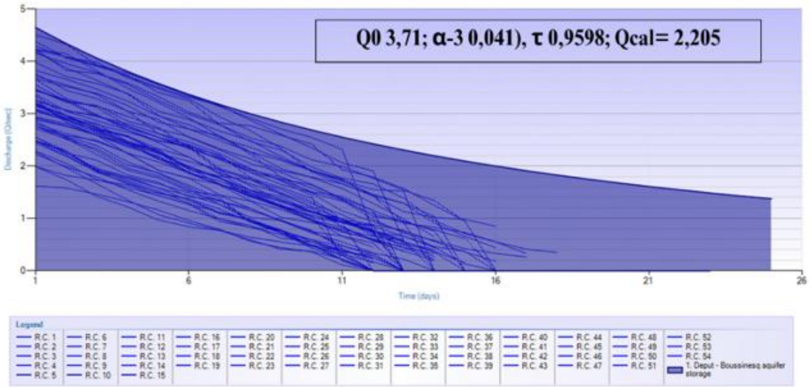

**Fig. 5.** MRC using Depuit-Boussinesq aquifer storage model for the Wae Batu Gantung Watershed.

Comparing the results from Wae Batu Gantung with those of other watersheds, such as Wae Batu Merah, Wae Ruhu, and Wae Batu Gajah, provides a deeper understanding of aquifer behavior in the region. While Wae Batu Gantung has a higher recession volume than Wae Tomu, its storage capacity remains lower than that of Wae Batu Merah, Wae Batu Gajah, and Wae Ruhu. This suggests that, although the amount of water stored in the Wae Batu Gantung aquifer is more significant than in Wae

Tomu, it is less effective at maintaining water over the long term. It is important to note that this analysis is relevant for regions facing significant fluctuations in rainfall or groundwater extraction, as the rapid changes in the Wae Batu Gantung Watershed indicate a higher dependency on sustainable water management. If groundwater extraction exceeds the aquifer's storage capacity, groundwater levels could rapidly decline, posing risks to the water supply.

The findings of this research have significant implications for effective groundwater management in Ambon and other small island regions. The Wae Batu Gantung Watershed, with its higher recession coefficient and lower storage capacity, requires extra attention in managing groundwater volume to prevent rapid declines in groundwater levels, which could disrupt water supply, especially during the dry season. By understanding the characteristics of this aquifer's recession, water resource managers can design more efficient extraction policies based on a deeper understanding of its storage capacity and response to changing conditions. For example, using the MRC model can help develop better water conservation strategies and support the construction of more sustainable water storage systems. The research on the Wae Batu Gantung Watershed shows that the aquifer in this region has a moderate storage capacity with a fast response to changes in flow or extraction. While the recession volume is higher than that of the Wae Tomu Watershed, its storage capacity is lower than that of other watersheds like Wae Batu Merah, Wae Batu Gajah, and Wae Ruhu, making it more vulnerable to faster groundwater level declines. This study provides valuable insights for planning and managing water resources in areas dependent on groundwater as a primary source, emphasizing the importance of understanding recession parameters to design more effective and sustainable management policies (Latuamury et al., 2024b).

### *3.1.5. MRC using Depuit-Boussinesq aquifer storage model for the Wae Tomu Watershed*

The recession parameter estimation for the Wae Tomu Watershed reveals distinct aquifer characteristics compared to other studied watersheds. The initial recession discharge ($Q_0$) for Wae Tomu was recorded at 4.19 $m^3/s$, higher than that of Wae Batu Gantung but lower than that of Wae Batu Merah, Wae Batu Gajah, and Wae Ruhu. The recession coefficient ($\alpha$-3) was 0.052, the recession constant ($\tau$) was 0.9493, and the flow volume (Q-Cal) was 2.0434 $m^3/s$. This indicates that the Wae Tomu Watershed releases more water initially than Wae Batu Gantung but less than watersheds with larger storage capacities, such as Wae Batu Merah and Wae Batu Gajah, as presented in **Fig. 6**.

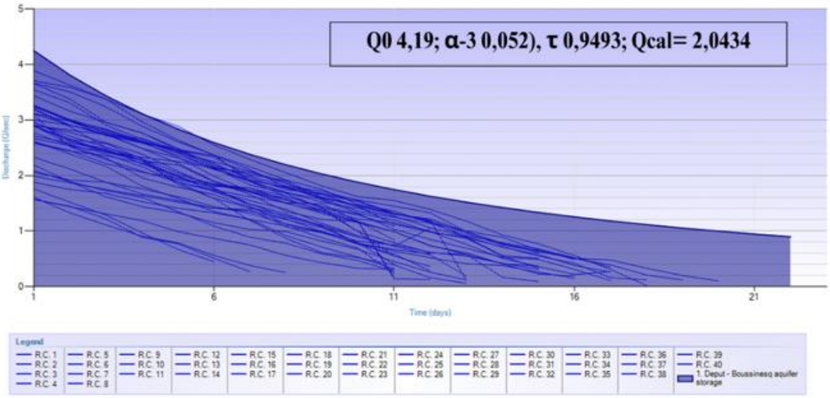

**Fig. 6.** MRC using Depuit-Boussinesq aquifer storage model for the Wae Tomu Watershed.

A significant finding from this study is that the Wae Tomu Watershed has a higher recession coefficient compared to all other watersheds (Wae Batu Merah, Wae Batu Gajah, Wae Batu Ruhu, and Wae Batu Gantung). A higher recession coefficient indicates that the groundwater head in Wae Tomu declines more rapidly after extraction stops. The Wae Tomu aquifer has a lower storage capacity and is more responsive to flow or rainfall cessation changes than other aquifers. The Material Recession Curve (MRC) for Wae Tomu shows a steeper decline, reflecting the aquifer's quicker response to changes. This is consistent with literature suggesting that aquifers with higher recession coefficients are more dynamic and sensitive to changes in flow or extraction (Latuamury et al., 2024b).

The recession constant ($\tau$) for Wae Tomu was 0.9493, lower than that of Wae Batu Merah, Wae Batu Gajah, and Wae Ruhu, indicating a lower storage capacity in the Wae Tomu aquifer. Additionally, the flow volume (Q-Cal) of 2.0434 $m^3/s$ suggests that the Wae Tomu aquifer stores less water per unit of head change than in other watersheds. The lower recession constant indicates that water in Wae Tomu's aquifer is released more quickly once extraction stops. Although the Wae Tomu aquifer releases water more rapidly, it has a lower capacity to maintain water reserves in the long term. Compared to other watersheds like Wae Batu Merah, Wae Batu Gajah, and Wae Ruhu, Wae Tomu has a higher initial discharge but a lower storage capacity. This means that while Wae Tomu releases more water initially than Wae Batu Gantung, it cannot store water more effectively over time than watersheds with larger capacities. This is a concern for areas with increasing extraction or long dry seasons, as the rapid depletion of groundwater could lead to shortages or drought. The findings highlight the need for careful water resource management in areas like Wae Tomu, where the aquifer has limited storage and responds quickly to extraction changes (Latuamury et al., 2024b). It is essential to regulate groundwater extraction to avoid depletion, and implementing rainwater harvesting or backup water storage systems could reduce dependence on the aquifer. Sustainable management strategies must balance extraction and conservation to protect groundwater, especially during fluctuating rainfall or extraction demands. The research provides valuable insights into the dynamics of the Wae Tomu aquifer, which is characterized by higher initial discharge, a higher recession coefficient, and lower storage capacity compared to other watersheds (Latuamury et al., 2024a). These findings stress the importance of understanding aquifer recession characteristics for designing sustainable water management strategies, especially in regions dependent on groundwater for their water supply.

### *3.2. The Shape of the Recession Curve Master of the Five Research Watersheds*

Studying groundwater flow dynamics within aquifers is fundamental for effective water resource management, especially in regions with limited freshwater availability, such as small islands. One of the most insightful methods to analyze groundwater flow is the Master Recession Curve (MRC) using the Depuit-Boussinesq Model (Aguilar et al., 2017; Malik and Bajtoš, 2017; Zhou et al., 2017). This approach integrates recession curve analysis with a hydrological model, providing a robust framework for understanding and predicting groundwater flow behavior during periods of extraction or recharge. Recession curves describe the decline in groundwater flow over time after an event of recharge, such as rainfall or artificial replenishment. The analysis of these curves plays a crucial role in understanding how aquifers respond to changes in hydrological conditions, such as variations in extraction rates or recharge events (Carlotto and Chaffe, 2019). In this study, we extended the application of the MRC by incorporating the Depuit-Boussinesq model to determine key parameters, including the recession coefficient (α) and recession constant (τ), which are essential for understanding an aquifer's storage capacity and discharge characteristics (Fatchurohman et al., 2018). These parameters are critical in forecasting how groundwater flow will evolve under different hydrological conditions. The recession coefficient determines the steepness of the recession curve. In contrast, the recession constant governs the duration of the groundwater head decline, thus measuring how long it takes for the aquifer to stabilize following a change in flow conditions (Nurkholis et al., 2019). Through this method, the MRC helps predict the long-term impacts of changes in extraction or recharge and enhances the ability to design more efficient and sustainable water management strategies.

The study of five different watersheds provides significant insights into groundwater behavior in various settings. Notably, the Wae Ruhu Watershed exhibited a higher recession constant, resulting in a more gradual decline in groundwater head, suggesting that the aquifer in this region has a larger storage capacity and responds more slowly to changes in extraction or recharge (Latuamury et al., 2023). Conversely, the Wae Batu Gantung and Wae Tomu Watersheds, with lower recession constants, displayed sharper and faster declines in groundwater heads. These findings are consistent with the understanding that aquifers with higher recession constants can sustain flow over a more extended period. In contrast, those with lower recession constants experience more rapid depletion, especially during dry periods (Latuamury et al., 2024b).

The recession coefficient also plays a vital role in shaping the recession curve. A higher recession coefficient results in a steeper curve, indicating that the aquifer responds more quickly to changes in flow conditions, while a lower coefficient implies a more gradual decline. This relationship between the recession coefficient and the speed of groundwater flow response is essential for predicting how an aquifer will behave during periods of extraction or recharge (Wijaya, 2022). The combined effect of the recession coefficient and constant allows for a nuanced understanding of how an aquifer will behave under different hydrological stress scenarios, such as increased water extraction or reduced recharge during droughts (Latuamury et al., 2022a).

Regarding practical implications, the findings emphasize the need to carefully manage groundwater resources, particularly in small island ecosystems where water resources are already scarce. Aquifers with high recession coefficients and low recession constants, such as those found in the Wae Batu Gantung and Wae Tomu Watersheds, exhibit rapid changes in groundwater levels in response to external influences. Such aquifers require more careful and dynamic management strategies to avoid over-exploiting. This could lead to severe consequences such as aquifer depletion or seawater intrusion in coastal areas (Lestari, 2023). Further, the study builds on existing research that has applied the Depuit-Boussinesq model in small island regions. Previous studies have shown similar patterns, where aquifers with higher recession coefficients exhibit more rapid declines in groundwater heads, highlighting the vulnerability of such aquifers to changes in hydrological conditions (Ahmad, 2020). Moreover, research by Lestari, 2023 in coastal aquifers in Karimunjawa Island underscores the importance of understanding the interactions between groundwater and seawater, especially in areas prone to saltwater intrusion. These insights are crucial for enhancing the sustainability of water resources in small islands, which are increasingly threatened by over-extraction and climate change. This study reinforces the importance of understanding the relationship between the recession coefficient, recession constant, and MRC shape in assessing an aquifer's response to hydrological changes. Variations in these parameters across different watersheds provide valuable insights into their storage capacities and response times. This information is essential for designing effective groundwater management strategies to address climate change, drought, and water scarcity challenges. Furthermore, the study highlights the relevance of integrating MRC analysis with the Depuit-Boussinesq model for informed decision-making in groundwater management, particularly in vulnerable small island regions. By leveraging these findings, we can better predict future groundwater behavior and develop strategies for more sustainable water use, ultimately enhancing the resilience of small islands to hydrological stress.

## 4. Conclusion

This study provides a deeper understanding of groundwater flow within aquifers using the Master Recession Curve (MRC) approach combined with the Depuit-Boussinesq model. The main findings indicate that the recession coefficient and constant are crucial in planning groundwater resource management, especially in small islands with limited water resources. Variations in these two parameters reflect the storage capacity and the aquifer's response to hydrological changes. Aquifers with high recession coefficients and low recession constants, such as those in the Wae Batu Gantung and Wae Tomu Watersheds, show rapid declines in groundwater heads, necessitating careful attention in sustainable groundwater management planning. This study has several limitations, including focusing on only five watersheds in small island regions, which may not fully represent conditions in other areas. The data used are limited to specific periods and conditions, affecting the accuracy of long-term predictions, especially in the context of climate change. The analysis did not fully incorporate other factors, such as groundwater quality, interactions with surface water bodies, and human activities. Additionally, the Depuit-Boussinesq model used has limitations in addressing complex or heterogeneous aquifer conditions. Future studies could integrate smart sensor technology and Geographic Information Systems (GIS) for more accurate and real-time data collection. The scope of research could also be expanded by including additional variables and developing more advanced models capable of handling aquifer geological heterogeneity and the impacts of climate change. Longitudinal monitoring is also essential to understand the long-term effects on aquifer resilience and groundwater resources in the future.

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