VOLUME 14 No. 1, 22 December 2024 Pages 1-17

MASTER RECESSION CURVE VISUALIZATION USING SEVEN BASEFLOW RECESSION MODELS IN PAIRED WATERSHEDS

VISUALISASI KURVA RESESI MASTER MENGGUNAKAN TUJUH MODEL RESESI BASEFLOW PADA DAS BERPASANGAN

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Submitted: 2023-11-15; Revised: 2024-05-20; Accepted:2024-06-08

ABSTRAK

Analisis resesi aliran sungai memiliki peran penting dalam memahami bagaimana daerah tangkapan air melepaskan air selama periode musim kering. Oleh karena itu, pemodelan resesi aliran dasar berkaitan erat dengan karakteristik akuifer bebas, penyimpanan, dan sifat debit DAS. Meskipun sudah terdapat beberapa teori tentang bagaimana memodelkan kurva resesi, namun penelitian yang membandingkan pendekatan berbeda terkait karakteristik resesi aliran baseflow masih terbatas. Penelitian ini bertujuan untuk memodelkan tujuh persamaan resesi aliran dasar pada DAS berpasangan di Kota Ambon. Metode penelitian melibatkan kalibrasi tujuh model resesi baseflow menggunakan perangkat lunak Recession Curve (RC) 4.0 HydroOffice. Model-model yang diuji meliputi Reservoir Linier, Reservoir Eksponensial, Eksponensial Ganda Horton, Penyimpanan Akuifer Dupuit-Boussinesq, Penyimpanan Detensi Depresi, Model Aliran Turbulen, dan Model Fungsi Hiperbolik. Hasil kalibrasi menghasilkan kombinasi parameter resesi yang optimal. Urutan parameterisasi dari tertinggi hingga terendah adalah model Depresi Tampung-Tahanan Simpanan, diikuti oleh model Fungsi Hiperbolik, Reservoir Eksponensial, Model Aliran Turbulen, Eksponensial Ganda Horton, Reservoir Linier, dan Tampungan Akuifer Dupuit-Boussinesq. Kuantifikasi konstanta dan koefisien resesi baseflow sangat penting dalam penelitian aliran dasar, terutama dalam karakterisasi perilaku baseflow. Visualisasi kemiringan Kurva Resesi (MRC) menunjukkan bahwa model dengan konstanta resesi tinggi cenderung memiliki MRC yang landai, sedangkan konstanta resesi rendah menghasilkan MRC yang curam. Kemiringan MRC menggambarkan hubungan antara kondisi penyimpanan dan pelepasan aliran dari wilayah tangkapan air. Keuntungan pembuatan MRC dari segmen resesi yang terputus-putus adalah kemampuannya untuk mendeskripsikan proses MRC secara sesuai dan memberikan parameter kuantitatif yang relevan dengan mekanisme drainase. MRC juga berfungsi sebagai alat komputasi otomatis yang optimal.

Keywords: *karakteristik akuifer; model resesi baseflow; DAS berpasangan; kapasitas simpanan.*

ABSTRACT

River flow recession analysis plays a crucial role in understanding how watersheds release water during dry periods. Consequently, modeling baseflow recession is closely related to the characteristics of unconfined aquifers, storage behavior, and the discharge properties of the watershed. While several theories exist on modeling recession curves, limited research has compared different approaches regarding baseflow recession characteristics. This study aims to model seven baseflow recession equations in paired watersheds in Ambon City. The research

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methodology involves calibrating seven baseflow recession models using the Recession Curve (RC) 4.0 Hydro Office software. The tested models include Linear Reservoir, Exponential Reservoir, Double Exponential Horton, Dupuit-Boussinesq Aquifer Storage, Depression Storage, Turbulent Flow Model, and Hyperbolic Function Model. The calibration results yield optimal combinations of recession parameters. The parameterization order from highest to lowest is as follows: Depression Storage, followed by the Hyperbolic Function, Exponential Reservoir, Turbulent Flow Model, Double Exponential Horton, Linear Reservoir, and Dupuit-Boussinesq Aquifer Storage. Quantifying baseflow recession constants and coefficients is essential for understanding baseflow behavior. Visualizing the slope of the Recession Curve (MRC) reveals that models with high recession constants tend to have gradual MRCs, while low recession constants result in steep MRCs. The MRC slope further describes the relationship between storage conditions and discharge from the watershed. The advantage of creating MRCs from discontinuous recession segments lies in their ability to appropriately describe the MRC process and provide quantitative parameters relevant to drainage mechanisms. MRCs also serve as an optimal automated computational tool.

Keywords: *aquifer characteristics; baseflow recession model; paired watersheds; storage capacity.*

INTRODUCTION

Baseflow is a watershed hydrological process associated with the release of groundwater into rivers and plays an essential role in the interactive activity between river flow and groundwater. The process is the primary source of river flow, mainly when there is no rainfall. A decrease in baseflow characterizes baseflow recession in a watershed due to inadequate water supply and groundwater recharge (Latuamury et al., 2020). The exploration of baseflow recession is essential for examining the properties of shallow aquifers in a catchment area. Understanding the dynamics of baseflow recession is crucial in water resource management, flood prediction, sediment transport, and drought assessment.

The characteristics of the recession process focused on spatial and temporal variability concerning hydrological behavior (Tashie et al., 2020). The baseflow recession curve contains information about the dynamic interactions between surface and groundwater and the hydraulic properties of unconfined aquifers. This curve also showed the observed rate of decline in streamflow between storm events, effectively representing the delay in streamflow storage within the catchment area.

However, analyzing a series of river flow recession periods is relatively complicated due to their unique nature (Lee et al., 2014). For example, after a storm, the downward hydrograph recession curve is characterized by a steep slope influenced by surface and subsurface flows. When this is not utilized, the curve shows a relatively low recession rate, resulting in weaker outflows (Hammond & Han, 2006; Latuamury et al., 2022). Spatial and temporal variations in initial groundwater storage and moisture conditions before the storm imply multiple recession curves with varying slopes.

The availability of comprehensive recession curves provides valuable information for understanding discharge-storage relationships in a particular catchment area (Aksoy & Wittenberg, 2015). During periods of recession, river recharge is closely related to streamflow, referred to as a constant, while the shape of the baseflow curve for all events tends to vary significantly. Several analytical baseflow methods and conceptual models have been studied, particularly the recession equation (Boussinesq, 1877; Horton, 1933; Maillet, 1905), continually modified and complemented by computer software.

Recent developments in baseflow recession models (Arciniega-Esparza et al., 2017) include the hydro recession method, performed with a Matlab toolbox for river flow analysis. This software applied three methods to extract hydrographic recession segments and analyzed the data using four general models (Aksoy & Wittenberg, 2011). Hydro recession tools provided valuable capacity for estimating both linear and nonlinear flow-storage relationship parameters, addressing a variety of regional needs, including catchment classification, baseflow separation, hydrological modelling, and low flow predictions (Arciniega-Esparza et al., 2017).

Understanding periods of river flow recession is fundamental for effective water resources management, as it controls the use of water supplies for human consumption, irrigation, and hydroelectric power generation. Baseflow must be considered in practice due to the ability to release groundwater into rivers during summer. The analysis of baseflow recession is closely related to the characteristics of unconfined aquifers, including the storage and discharge properties of the watershed flow.

However, challenges such as low quality of baseflow data, high variability of recession curves, and limitations in mathematical methods can hinder the determination of watershed-scale characteristics. To tackle these challenges, three different methods, namely analytical expressions, graphical methods for determining master recession curve (MRC), and parameterization based on baseflow recession rate as a function of flow, were adopted (Sujono et al., 2004).

MRC is a graphical method that depends on overlapping recession curves, where individual segments are plotted and adjusted to form a single representation of data (Latuamury et al., 2020; Latuamury et al., 2022). This method served as an alternative to address the variability of each recession period by considering several curves extracted over a long period. However, MRC is limited in representing flow storage variations, making identifying transition points of fast and slow flow components difficult. To provide a comprehensive analysis, parameterization based on recession curves was conducted, considering flow variability. Several research had used least squares regression with different mean flow data for this purpose (Boughton, 2015). Furthermore, Stoelzle et al. (2013) used different methods to improve the interpretation of recession behavior at the watershed scale and obtained significant variations in analyzing related characteristics.

Advances in computational resources have led to the development of toolboxes that combined various recession analysis methods, which enabled the consistent evaluation of watershed characteristics and facilitated the comparison of multiple parameterizations. Recent research (Arciniega-Esparza et al., 2017) developed a MATLAB toolbox containing standard methods for assessing recessions based on analytical expressions. Tashie, Pavelsky, and Emanuel (2020) used this toolbox to analyze baseflow recession. Rupp and Selker (2006) developed an automated method to separate MRC into two or three sections based on a defined flow duration curve. Subsequently, five different regression models were adopted to formulate MRC and obtain parameters using the exponential model. Carlotto & Chaffe (2019) contributed to this field by developing the MATLAB-based MRCPTool, which provided an automated resource for analyzing recession periods based on river flow data.

The tool compared recession analysis methods and parameterizations based on various analysis models. MRCPTool also has a graphical user interface (GUI) that offers automated resources for performing hydrograph splitting using numerical filters, automatic extraction of recession periods, and developing MRC with appropriate strip methods for different flows determined from duration curves, and rate analysis. Generally, flow recession includes generating MRC from simulated recession curves using linear and nonlinear analysis methods.

In Ambon City, a small island, the gradual decline in river discharge following runoff or flow recession was studied to estimate the basin processes. The ability of watersheds to store and release runoff water is considered for reliable prediction of seven recession models and effective water resource management. Hydro Office 12.0 software, specifically the Recession Curve (RC) 4.0 package, was used to estimate characteristic parameters for baseflow recession modelling and MRC visualization of the entire model (Gregor & Malík, 2012). Based on the superior working mechanism of the RC 4.0 package, this research aimed to calibrate seven baseflow recession models for paired watersheds in Ambon City. The objective was to assess storage relationships, and outflow discharge, responsible for characterizing flow dynamics in the catchment area.

METHOD

Research Area

The research areas, namely Wae Batu Gajah and Wae Tomu, were in the paired watershed of Ambon City. The regional description of the two watersheds was based on morphometric characteristics such as area, average slope, river slope, main river length, circulation, and branching ratios, including flow patterns. These parameters show the relationship between morphometry and hydrological characteristics, including drainage density, branching and bifurcation ratios. Furthermore, morphometric parameters significantly influence watershed management, specifically flood vulnerability and baseflow storage.

The morphometric and hydrological characteristics of Wae Batu Gajah and Wae Tomu have relatively similar drainage density parameters, ranging from one to five, showing good management. A less than one branching ratio depicts abnormal river basin conditions characterized by high flood peaks and short recession times. This condition tends to have heightened flood vulnerability, including low permeability and infiltration due to high surface flow. Analysis of the branching ratio showed that the shape of the two paired watersheds is elongated, leading to slow peak discharge (Qp) and increased recession time (Latuamury et al., 2021). Additionally, these morphometric characteristics are shown in Table 1 and Figure 1.

Table 1.
Morphometric characteristics of Wae Batu Gajah and Wae Tomu watersheds

Watershed name	Area (km^2)	Average Slope (m)	River Gradient (m)	Length of main river (km)	Drainage Density (km/km^2)	Circulation Ratio (CR)	Bifurcation Ratio (BR)	Flow pattern
Wae Batu Gajah	6.35	0.49	324.98	6.58	2.91	12.56	0.95	Dendritic
Wae Tomu	5.62	4.89	349.98	6.14	3.16	5.47	0.93	Dendritic

Source: Image analysis, 2019

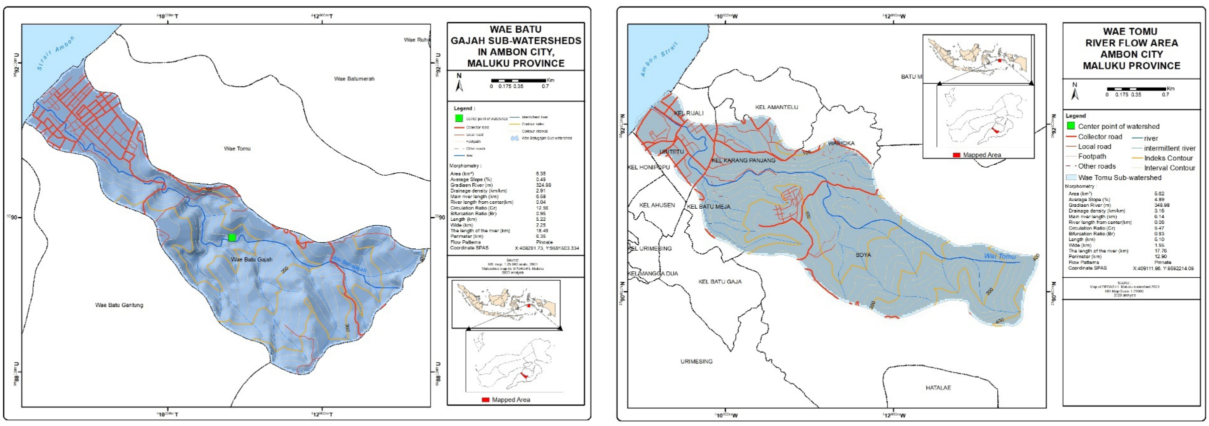

Figure 1.
Paired watershed morphometric map of Wae Batu Gajah (top) and Wae Tomu (bottom) of Ambon City
Source: Author (2023)

Collected Data

River flow records with good temporal resolution provided valuable information for understanding catchment characteristics. This research used daily discharge from two river flow measurement stations in Pulau Kecil Watershed of Ambon City to separate and select the recession segment. Furthermore, the availability of daily discharge from 2007 to 2014 was sufficient to conduct baseflow recession analysis.

Baseflow recession analysis

Recession analysis was used to examine parts of the flow hydrograph relating to the relationship between the aquifer structure and groundwater discharge into the river. The analysis was carried out using Hydro Office 12.0 software, specifically the RC.4.0 package, by calibrating seven baseflow recession models (Gregor & Malí k, 2012), as shown in Table 2.

Table 2.
Baseflow recession models using Hydro Office 12.0 software, RC.4.0 package

Conceptual model	Recession function	Storage type
Linear reservoir (Joseph Boussinesq, 1877; Maillet, 1905)	$Q = Q_0 e^{-kt}$	General storage, Linearized Depuit-Boussinesq equation, approximation for short time periods
Exponential reservoir	$Q = Q_0/(1 + \emptyset Q_0 . t)$	Throughflow in soil, hydraulic conductivity assumed to exponentially decrease with depth
Horton double exponential model (Horton, 1933)	$Q = Q_0 e^{-\alpha_2 t^m}$	General storage, the transformation of the linear reservoir model
Dupuit-Boussinesq aquifer storage (J Boussinesq, 1877)	$Q = Q_0(1 + \alpha_3 t)^{-2}$	Shallow unconfined aquifer, a special case of power-law reservoir for Dupuit-Boussinesq aquifer model
Depression-detention storage (Griffiths & Clausen, 1997)	$Q = \alpha_1/(1 + \alpha_2 t)^3$	Surface depressions such as lakes and wetlands, a variant of power-low reservoir
Turbulent model (Kullman, E., 1990)	$Q = Q_0(1 - \beta t)$	Karstic aquifers
Hyperbolic function model (Kovács, 2003)	$Q = Q_0(1 + \alpha t)^n$	Karstic aquifers

Source: Gregor, M. and Malík (2012)
Note: Q= discharge, t= time since beginning of recession, Q_0= discharge for t =0, k, n, α, β, ϕ - parameters to be determined by calibration

The recession analysis of river flow data from observed hydrographs enabled the extraction of information regarding the storage-outflow relationship between the catchment and hydraulic properties of the groundwater. Hydro Office 12.0 software, specifically the RC.4.0 package with a graphical user interface, was used to conduct the analysis, facilitating the calibration of seven different baseflow recession models. The calibration results were used to obtain MRC from each model, which was then compared across the Wae Batu Gajah and Wae Tomu watersheds in Ambon City, Maluku, Indonesia.

RESULTS AND DISCUSSION

Calibration results of the linear reservoir model for master recession curve

The evaluation of recession characteristics at the two river flow measurement stations included MRC and separation analysis using seven baseflow models. The process comprised identifying and isolating various segments from the hydrograph data and calculating baseflow recession characteristics for each watershed. Hydrograph data were interpreted to assess watershed flow storage conditions, and the shape of MRC was analyzed using seven recession models. The calibration results provided a set of calculated recession parameters, as shown in Table 3.

The parameters of the two watersheds were calculated using seven recession models. Based on the results of storage depression-storage, the highest and lowest initial recession discharge was obtained in Wae Batu Gajah (4.85 m^3/sec), and Wae Tomu watersheds (3.27 m^3/sec), respectively.

Table 3.
Calculation of recession parameters for the seven baseflow recession models in two paired watersheds

Baseflow recession model		Initial discharge of recession	Recession coefficient	Recession constant	Q-obs	Q-cal
Linear reservoir	Wae Batu Gajah	4.65	0.065	0.9371	4.65	4.36
	Wae Tomu	3.99	0.0799	0.9232	4.19	3.68
Exponential reservoir	Wae Batu Gajah	4.65	0.016	0.9545	4.65	4.44
	Wae Tomu	4.651	0.033	0.9535	4.45	4.99
Horton double exponential	Wae Batu Gajah	4.65	0.064	0.9380	4.61	4.36
	Wae Tomu	3.99	0.0799	0.9036	4.00	3.74
Dupuit-Boussinesq aquifer storage	Wae Batu Gajah	4.65	0.035	0.9335	4.65	4.34
	Wae Tomu	4.19	0.052	0.9335	4.10	3.92
Depresion storage-Detention storage	Wae Batu Gajah	4.85	0.026	0.9771	4.85	4.77
	Wae Tomu	3.27	0.0345	0.9800	4.33	3.53
Turbulent flow model	Wae Batu Gajah	4.55	0.0491	0.9509	4.55	4.33
	Wae Tomu	3.89	0.051	0.9490	3.88	3.70
Hyperbolic function model	Wae Batu Gajah	4.65	0.076	0.9747	4.65	4.53
	Wae Tomu	4.23	0.099	0.9560	4.00	4.55

Source: Recession parameters using Hydro office 12.0 RC 4.0 (2023)

In Wae Tomu and Wae Batu Gajah watersheds, hyperbolic function and exponential reservoir models obtained the highest (0.099), and lowest recession coefficients (0.016), respectively. Meanwhile, in Wae Tomu watershed, the storage depression-storage detention and Horton double exponential models obtained the highest values of 0.9800, and 0.9036.

The average results of the statistical calculations were dependent on the combination of the three baseflow recession parameters for each model. For example, the highest average baseflow recession showed that the storage depression-storage detention model obtained 2,689 m^3/sec in Wae Tomu watershed, while the Horton double exponential yielded a different value recorded in m^3/sec. The seven models varied significantly in combination with recession parameters and average baseflow values for both watersheds, as shown in Table 4.

Table 4.
Descriptive statistics of baseflow recession mean for seven models

Baseflow recession model		N	Minimum	Maximum	Sum	Mean	Std. Deviation	Variance	Skewness	Kurtosis
Linear reservoir	Wae Batu Gajah	25	0.98	4.65	59.33	2.373	1.1124	1.237	0.586	-0.797
	Wae Tomu	22	0.55	4.19	39.95	1.816	1.1023	1.216	0.765	0.953
Exponential reservoir	Wae Batu Gajah	25	1.67	4.65	67.22	2.689	.8671	0.752	0.810	-0.322
	Wae Tomu	22	1.04	4.45	44.25	2.011	00.956	0.915	1.205	0.953
Horton double exponential	Wae Batu Gajah	25	0.99	4.61	59.36	2.375	1.0947	1.198	0.576	-0.807
	Wae Tomu	22	0.67	4.00	41.48	1.886	1.0117	1.024	0.678	0.953
Dupuit-Boussinesq aquifer storage	Wae Batu Gajah	25	1.37	4.65	63.69	2.548	.9715	0.944	0.709	-0.556
	Wae Tomu	22	1.00	4.10	44.96	2.043	.9182	0.843	0.845	0.953
Depresion storage - Detention storage	Wae Batu Gajah	25	1.13	4.85	60.91	2.436	1.1024	1.215	0.750	-0.493
	Wae Tomu	22	0.75	4.33	41.92	1.905	1.0587	1.121	0.924	0.953
Turbulent flow model	Wae Batu Gajah	25	0.08	4.55	48.64	2.316	1.3863	1.922	0.000	-1.200
	Wae Tomu	22	0.12	3.88	41.48	1.885	1.1735	1.377	0.193	0.953
Hyperbolic function model	Wae Batu Gajah	25	1.65	4.65	66.69	2.668	0.8731	0.762	0.822	-0.304
	Wae Tomu	22	1.33	4.00	48.82	2.219	0.778	0.605	0.887	0.953
Valid N (listwise)	Wae Batu Gajah	25								
	Wae Tomu	22								

Source: Data analysis using SPSS (2007-2014)

Baseflow statistics are used to determine the annual average baseflow of a river during a specific return period. When sufficient historical records exist for a particular catchment area, these statistics can be obtained through the frequency analysis of observed river flow data. However, in cases where river flow records are insufficient, a regional method was applied for estimation purposes (Latuamury et al., 2022). Accurate estimates of the frequency of baseflow recession events and spatio-temporal evolution in water catchments are relevant to engineers and water managers (Dewandel et al., 2006).

Estimation of baseflow recession parameters and MRC Visualization of Linear reservoir model

A linearized equation was formulated by Boussinesq (1877) to estimate baseflow recession periods using relatively short-flow data. This research used model calibration for paired watersheds to assess stream storage capacity for daily discharge data from 2007 to 2014. However, the graphical interpretation of recession segments to separate MRC using a linear reservoir model showed that the segments were consistent with the model, appearing as straight lines parallel to the semi-log graph.

In the Wae Batu Gajah watershed, a combination of recession parameters with initial recession discharge (Q0) and constant of 4.65 m^3/second and 0.9371, including α value of 0.065, were obtained. Meanwhile, the values obtained in Wae Tomu were 3.99 m^3/second, 0.9232, and 0.79. The recession constant parameterization results showed that the MRC slope in the two paired watersheds was relatively different. Specifically, the slope of MRC of the Wae Batu Gajah watershed (k= 0.9371) was relatively gentle compared to Wae Tomu (k=0.9232). MRC slope was visualized using a linear reservoir model for the two relatively sloping watersheds, as shown in Figure 2.

The exponential relationship between storage and outflow is represented by a straight line parallel to the Q versus time plane, as shown in Figure 2. The paired watershed MRC has a relatively gentle slope, suggesting good storage characteristics in the aquifer. The linear reservoir model was used to determine baseflow characteristics, which function as a predictor in the regional recession model.

The predictors derived from linear and nonlinear models were used separately in regional baseflow models, representing physiographic and meteorological characteristics. These models were applied to the measured water catchment area. In the present research, the best performance estimation results were obtained from the recession parameters of the linear model. However, one disadvantage of using recession parameters to estimate the regional baseflow model is the need for river flow recording at the location of interest. This parameter can also be estimated from relatively short river flow records such as those which occurred in a year. Models with recession parameters from nonlinear models performed better than those with physiographic and meteorological characteristics (Latuamury, 2018; Latuamury et al., 2022).

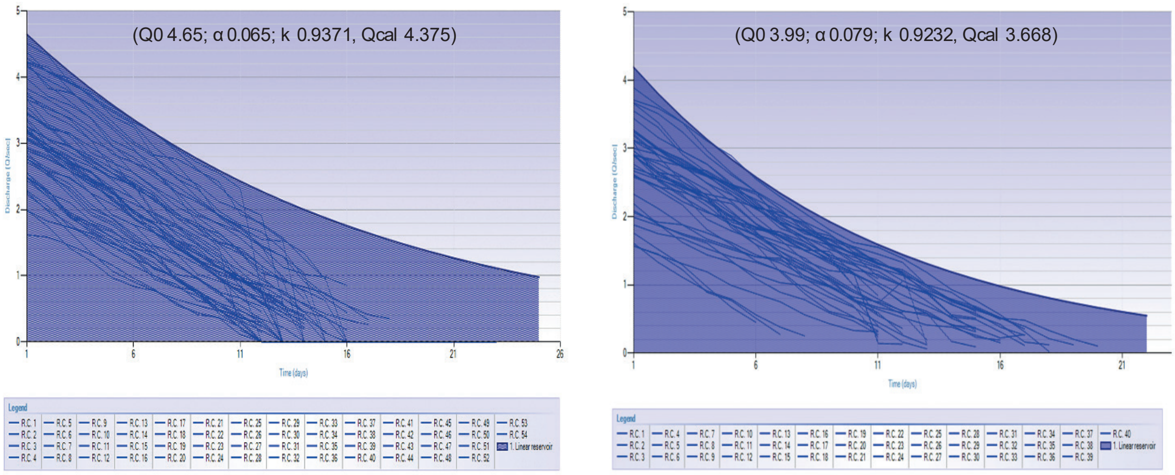

Figure 2.
MRC Visualization of Linear reservoir model for Wae Batu Gajah (left) & Wae Tomu (right)
Source: Model calibration using hydro office module RC.4.0 (2023)

Estimation of baseflow recession parameters and MRC Visualization of Exponential reservoir model

The results of the second recession calibration obtained using an exponential reservoir model had a different combination of parameters, including initial recession discharge (Q0), coefficient value ϕ, and constant compared to the first model. The Wae Batu Gajah watershed results included initial recession discharge, ϕ value and constant of 4.65 m^3/second, 0.016, and 0.9545, respectively. Meanwhile, Wae Tomu obtained initial recession discharge, ϕ value and constant of 4,651 m^3/second, 0.033, and 0.9535. These results showed that the two paired watersheds had relatively similar MRC slopes, with recession constant (k) values of 0.9545 and 0.9535, respectively. Visualization of the MRC slope using an exponential reservoir model showed that the MRC of both watersheds was relatively gentle compared to the linear reservoir model, as shown in Figure 3.

The exponential reservoir model described groundwater flow, assuming hydraulic conductivity decreased gradually with increasing depth. This method is widely applied in recession curve analysis as an approximate analytical solution to the diffusion equation in porous media. However, the equation proposed by Boussinesq described baseflow recession in a quadratic form, providing adequate qualitative data regarding the characteristics of the aquifer (Botter et al., 2009).

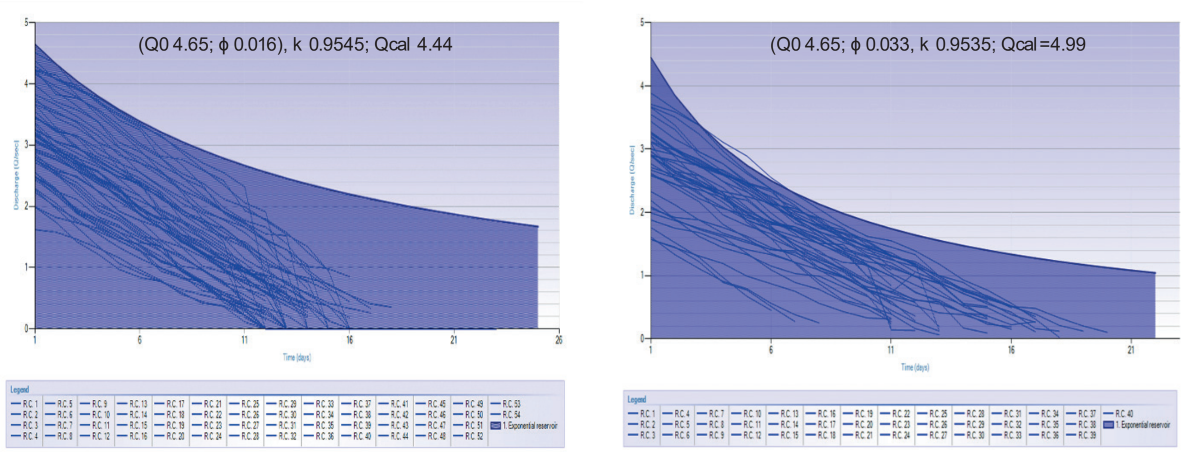

Figure 3.
MRC Visualization of Exponential reservoir model for Wae Batu Gajah (left) & Wae Tomu
Source: model calibration using hydro office module RC.4.0 (2023)

Estimation of baseflow recession parameters and MRC Visualization of Horton double exponential

The calibration of the Horton double exponential model was a combination of recession parameters, including initial recession discharge (Q0), coefficient value α-2, and m, which functioned as a constant. This constant tends to be steeper compared to linear and exponential reservoir models. The initial recession discharge, α-2 value, m and constant obtained from the Wae Batu Gajah watershed were 4.65 m^3/second, 0.064, 1, and 0.9380, respectively. Meanwhile, the values obtained at Wae Tomu were 3.99 m^3/second, 0.079, 1, and 0.9036. These results showed that the MRC slope was relatively different, with the Wae Batu Gajah watershed (k 0.9380) being steeper than the Wae Tomu (k 0.9232). The visualization of the MRC slope using the Horton double exponential model was relatively steeper than those generated by the linear and exponential reservoir models, as shown in Figure 4.

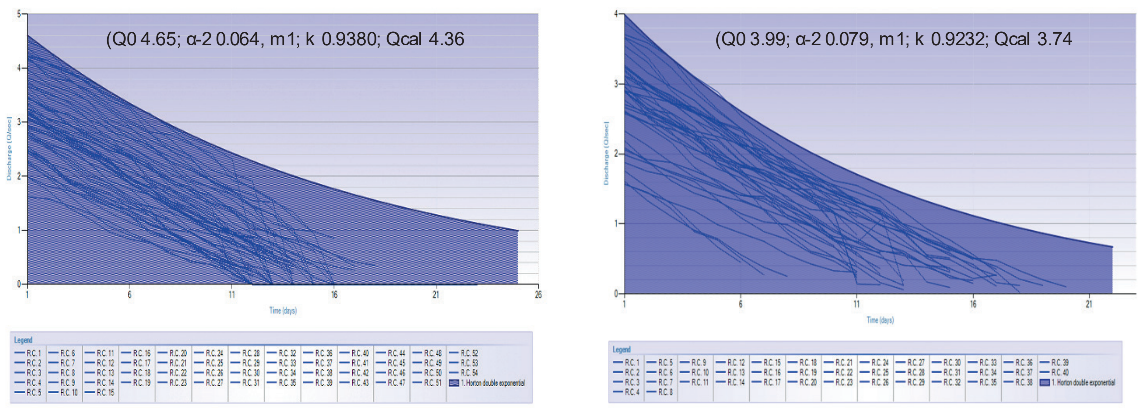

Figure 4.
MRC Visualization of Horton double exponential for Wae Batu Gajah (left) & Wae Tomu (right)
Source: model calibration using hydro office module RC.4.0 (2023)

The Horton double exponential model was used to describe the general storage of a catchment derived from the transformation of a linear reservoir model. The structure of the river flow system is in line with the Horton law regarding the number and length of flows. According to Horton (1933), the general model represents the exponential relationship between hydraulic head and flow rate. Bartlett and Porporato (2018) stated that aquifer system discharge was characterized by nonlinear behaviour. Consequently, it is crucial to explore various linear and nonlinear, including other models, to analyze recession curves in specific catchment areas effectively.

Estimation of baseflow recession parameters and MRC Visualization of Depuit-Boussinesq Aquifer Storage

The Depuit-Boussinesq aquifer storage model is a baseflow recession model used to describe shallow groundwater aquifers and confined zones. It applied the power-law reservoir equation to the Depuit–Boussinesq aquifer model (Latuamury et al., 2020; Şener et al., 2020). The hydrological characteristics of the watershed were described based on time and volume factors determined from the baseflow recession curve. Generally, the curves were generated by plotting flow measurements against time based on the assumption of no recharge to the groundwater reservoir after rainfall events. The volume factor on the recession curve, representing the total potential discharge, varies directly with the depth of the main channel and the relief of the basin and inversely with the maximum width. Deep drains tend to function as more efficient drainage outlets, particularly narrow drains. A high relief ratio also reflected an increase in peak volume, rainfall, filling, and discharge (Nurkholis et al., 2019).

The calibration results of the fourth recession model using Dupuit-Boussinesq aquifer storage obtained a combination of parameters, including initial recession discharge (Q0), α-3 coefficient value, and relative constants, which varied between the two paired watersheds. The initial recession discharge, α-3 value, and constant obtained at the Wae Batu Gajah watershed were 4.65 m^3/second, 0.035, and 0.9335, respectively. Meanwhile, Wae Tomu obtained initial recession discharge, α-3 value, and constant of 4.19 m^3/second, 0.052, and 0.9036, respectively. These results showed that the two paired watersheds were relatively different.

MRC slope, with relatively varying recession constant (k) values of 0.9335 and 0.9036 for the respective watersheds. The visualization of the MRC slope using the Dupuit-Boussinesq aquifer storage model was similar to the linear reservoir and Horton double exponential models. However, significant differences were observed compared to the exponential reservoir model, as shown in Figure 5.

The simulation of a shallow aquifer with an impermeable layer at the outlet level showed that the recession curve was quadratic. However, the Maillet solution significantly overestimated the duration and volume of dynamic aquifers (Stoelzle et al., 2013). The Boussinesq equation was used to estimate aquifer parameters accurately. Realistic numerical simulations of an aquifer with a deeper impermeable layer located at the outlet proved the reliability of the Boussinesq equation under certain conditions, deviating from the simplifying assumptions used to integrate the diffusion equation.

The quadratic recession equation remained valid regardless of thickness (Latuamury et al., 2021). The aquifer beneath the outlet reasonably estimated the hydrodynamic parameters, particularly for those with intense layers, yielding exponential recession curves. Following the Maillet equation, this configuration fit the recession curve, showing exponential behaviour when vertical and horizontal flow components were significant and quadratic. Consequently, the aquifer's permeability changed the recession curve's shape (Şener et al., 2020).

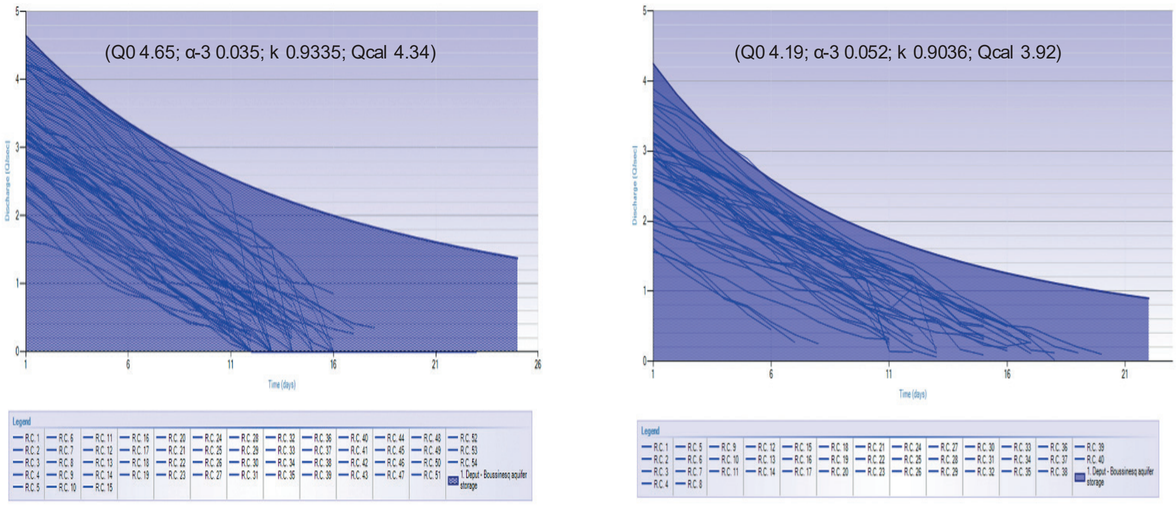

Figure 5.
MRC Visualization of Dupuit-Boussinesq aquifer storage untuk Wae Batu Gajah (left) & Wae Tomu (right)
Source: model calibration using hydro office module RC.4.0 (2023)

Estimation of baseflow recession parameters and MRC Visualization of Depression storage-detention storage

The storage-detention depression storage model, a variant of the power law equation, described surface water basins such as lakes and wetlands. These models are essential in hydrology, specifically for characterizing and predicting baseflow rates during the dry season. Furthermore, the characterization was used to determine the possibility of storing and using surface water resources for drinking, irrigation, and industrial usage and the impact of pollution on downstream waste disposal areas. The final recession section focused on aquifer discharge, providing data on the structure and function, particularly concerning hydrodynamic parameters such as permeability and coefficients.

Calibration of the fifth recession model using depression storage-detention storage led to a combination of parameters, including initial recession discharge (Q0), α-2 coefficient value, and the same relative constant for both paired watersheds. The initial recession discharge, α-2 value, and constant obtained for the Wae Batu Gajah watershed were 4.85 m^3/second, 0.026, and 0.9771. Meanwhile, Wae Tomu had an initial recession discharge, α-2 value and constant of 3.27 m^3/second, 0.0345, and 0.9800, respectively. These results showed that the paired watersheds had MRC slopes with relatively similar recession constant values. The visualization of storage depressions revealed a pronounced sloping MRC shape with the highest recession constant, followed by an exponential reservoir, Dupuit-Boussinesq aquifer storage, linear reservoir, and Horton double exponential models, as shown in Figure 6.

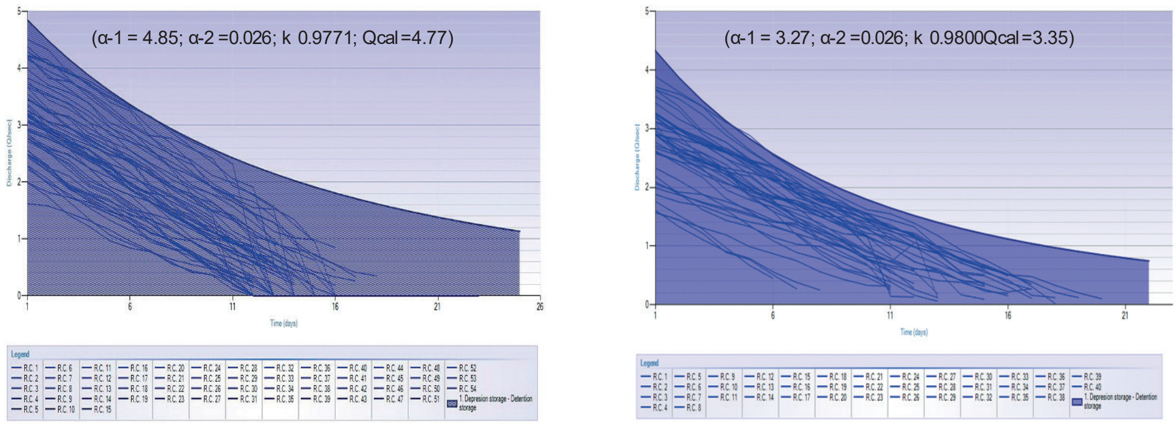

Figure 6.
MRC Visualization of Depression Storage-Detention storage for Wae Batu Gajah (left) & Wae Tomu (right)
Source: model calibration using hydro office module RC.4.0 (2023)

Estimation of baseflow recession parameters and MRC Visualization of Turbulent flow model

MRC visualization carried out with the calibration of the sixth recession model, especially the turbulent flow model, obtained a similar combination of initial recession discharge (Q0), β coefficient values, and relative constants for both paired watersheds. The initial recession discharge, β value and constant of the Wae Batu Gajah watershed were 4.55 m^3/second, 0.049, and 0.9509. Meanwhile, Wae Tomu obtained an initial recession discharge, β value and constant of 3.89 m^3/second, 0.051, and 0.9490, respectively. These results showed that the paired watersheds had MRC slopes with relatively similar recession constant values. Visualization of the MRC slope through the depression-detention storage showed a sloping MRC shape with a relatively high recession constant. Furthermore, the MRC slope generated with the turbulent flow model was relatively similar to the exponential, Dupuit-Boussinesq aquifer storage, linear reservoir, and Horton double models. It differed from the Detention Storage Depression storage, as shown in Figure 7.

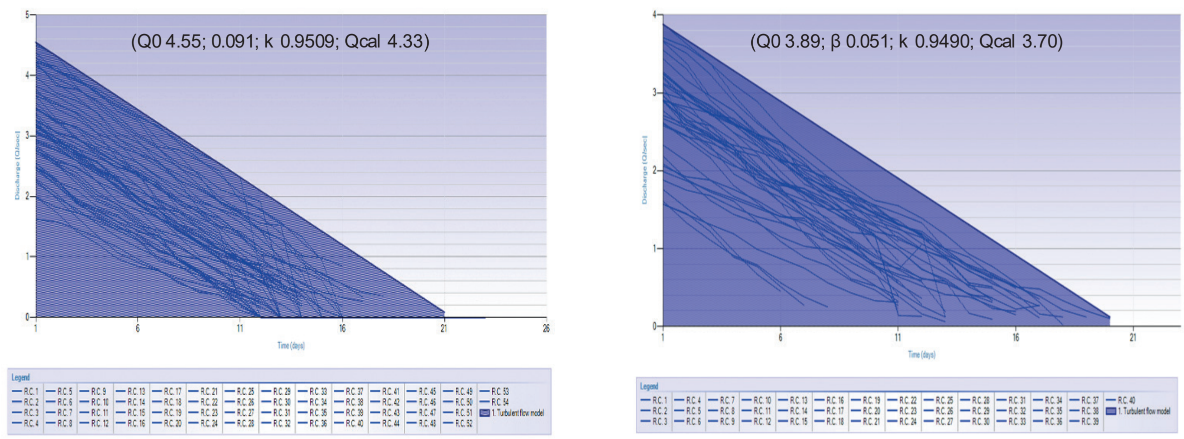

Figure 7.
MRC Visualization of Turbulent flow model for Wae Batu Gajah (left) & Wae Tomu (right)
Source: model calibration using hydro office module RC.4.0 (2023)

The turbulent flow model was designed for karst aquifers (Fatchurohman et al., 2018), characterized by the transition from an initially relatively homogeneous porous flow to a highly heterogeneous and controllable pattern in the future. During the initial karstification phase, the flow was confined in the permeable rock matrix along interconnected fractures separating distinct blocks. The minimum initial fracture width played an essential role in determining the conductivity of a rock with a matrix of the same magnitude. This was because fractures in karst aquifers enlarge over time due to chemical dissolution, causing more flow restrictions. Therefore, flow in karst aquifers characterizes efficient drainage through fractures, which become cavernous and highly heterogeneous systems of considerable size (Gregor & Malík, 2012).

Estimation of baseflow recession parameters and MRC Visualization of Hyperbolic function model

Calibrating the seventh recession model using the Hyperbolic function model obtained a combination of parameters, including initial discharge (Q0), α coefficient value, and the same relative constant for both paired watersheds. The α value and constant associated with the initial recession discharge of the Wae Batu Gajah watershed were 4.65 m^3/second, 0.076, and 0.9747, respectively. Meanwhile, Wae Tomu α value and a constant of 4.23 m^3/second, 0.099, and 0.9560. These results showed that the paired watersheds had MRC slopes with relatively similar constants. Visualizing the Hyperbolic MRC function model, the slope appeared steep, ranking second after the Depression storage-detention model. This was followed by the exponential reservoir model, turbulent flow, linear reservoir, Horton double exponential, and Dupuit-Boussinesq aquifer storage model, shown in Figure 8.

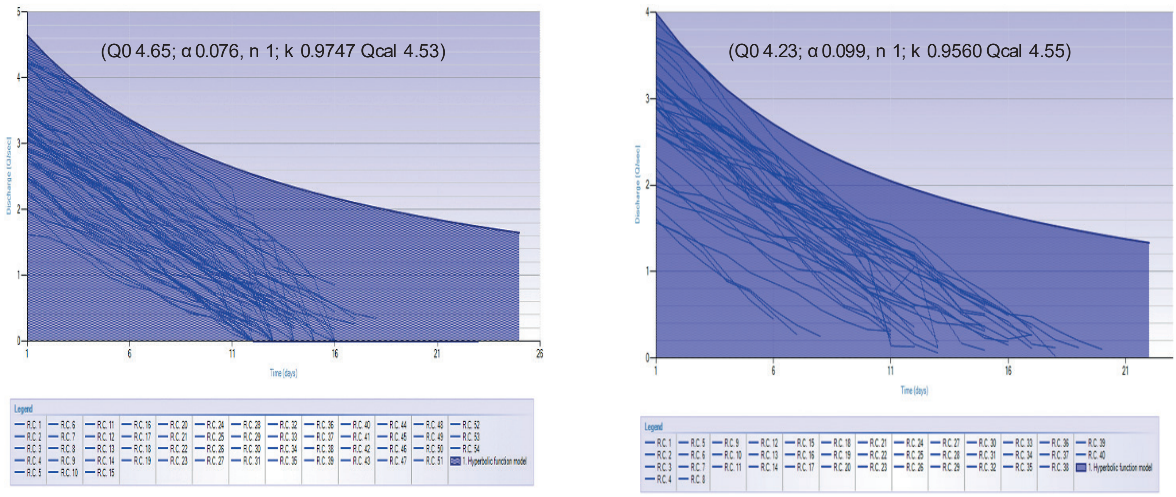

Figure 8.
MRC Visualization of Hyperbolic function model for Wae Batu Gajah (left) & Wae Tomu (right)
Source: model calibration using hydro office module RC.4.0 (2023)

The hyperbolic function model was also used to describe the condition of karst aquifers. Additionally, recession analysis of karst springs is widely used to characterize aquifer types (Basha, 2020). The response of an aquifer to recharge was characterized and modelled using a transfer function, which determined the storage system's peak response time, distribution, and total duration. Determining groundwater recharge areas for karst springs was necessary for estimating groundwater availability and identifying contaminant sources and movement (Endres et al., 2007). Baseflow recession analysis provided insight into the characteristics of MRC by examining each recession segment using adequate adjustments to obtain the optimal shape. Seven recession models were used to describe variations between segments, reflecting the differences in initial discharge from the catchment aquifer and flow losses due to evapotranspiration processes. Several research had contributed to improving the prediction of regional baseflow characteristics by including recession parameters that describe the catchment area (Adji et al., 2017).

They calibrated these seven baseflow recession models to determine the most suitable model for the paired watersheds. In principle, these models generally fit the MRC recession curve with exponential and quadratic models rather than numerical simulations. MRC visualization was similar, characterized by a gradual decrease in flow rate over time. However, dissimilarities were also observed between water catchment areas such as aquifers or springs (Nurkholis et al., 2019). Hydrodynamic properties, such as hydraulic conductivity and gradient, including storage coefficient, influenced the shape of the MRC curve.

CONCLUSION

In conclusion, the calibration results of the seven recession models based on parameters showed that the initial discharge values, constants, and coefficients for the paired watersheds were relatively similar. On optimizing the best models based on recession constants, the rankings were as follows: Depression storage-detention storage, Hyperbolic function model, Exponential reservoir, Turbulent flow model, Horton double exponential, Linear reservoir, and Dupuit-Boussinesq aquifer storage. The calculated results of the highest baseflow recession volume for the seven models in the Wae Tom watershed was 4.99 m^3/second. The results obtained showed variations in the MRC slope of each model, with Depression Storage-Detention Storage showing a steep slope, followed by Hyperbolic function, Exponential Reservoir, Turbulent Flow Model, Horton Double Exponential, Linear Reservoir, and Dupuit-Boussinesq Aquifer Reservoir. MRC slope visualization showed the relationship between storage conditions and outflow in the paired watersheds, showing optimal flow absorption, storage and channeling capabilities in both seasons. Due to the complex nature of the fractured rock aquifer system in the catchment area and the limited hydrogeological information available, the interpreted results regarding physical and hydrogeological properties and the control of river flow and baseflow recession posed a complex problem. Therefore, further research was recommended to test and refine the baseflow recession model, address the implementation uncertainties and apply the model to several perennial and ephemeral rivers to compare the characteristics

ACKNOWLEDGEMENTS

The authors are grateful to the River Basin Office of Maluku Province and the Ministry of Public Works, Indonesia, for providing access to hydrological data during the research period. The authors are also grateful to the Ministry of Education, Culture, Research and Technology, Directorate General of Higher Education, Research and Technology, Indonesia, for providing adequate funding.

BIBLIOGRAPHY

Adji, T. N., Haryono, E., Fatchurohman, H., & Oktama, R. (2017). Spatial and temporal hydrochemistry variations of karst water in Gunung Sewu, Java, Indonesia. *Environmental Earth Sciences*, *76*(20). https://doi.org/10.1007/s12665-017-7057-z

Aksoy, H., & Wittenberg, H. (2011). Analyse non linéaire des récessions de l'écoulement de base dans des bassins versants à écoulements intermittents. *Hydrological Sciences*

Journal, *56*(2), 226–237. https://doi.org/10.1080/02626667.2011.553614

Aksoy, H., & Wittenberg, H. (2015). Baseflow Recession Analysis for Flood-Prone Black Sea Watersheds in Turkey. *Clean - Soil, Air, Water*, *43*(6), 857–866. https://doi.org/10.1002/clen.201400199

Arciniega-Esparza, S., Breña-Naranjo, J. A., Pedrozo-Acuña, A., & Appendini, C. M. (2017). HYDRORECESSION: A Matlab toolbox for streamflow recession analysis. *Computers and Geosciences*. https://doi.org/10.1016/j.cageo.2016.10.005

Bartlett, M. S., & Porporato, A. (2018). A Class of Exact Solutions of the Boussinesq Equation for Horizontal and Sloping Aquifers. *Water Resources Research*, *54*(2), 767–778. https://doi.org/10.1002/2017WR022056

Basha, H. A. (2020). Flow Recession Equations for Karst Systems. *Water Resources Research*, *56*(7), 1–21. https://doi.org/10.1029/2020WR027384

Botter, G., Porporato, A., Rodriguez-Iturbe, I., & Rinaldo, A. (2009). Nonlinear storage-discharge relations and catchment streamflow regimes. *Water Resources Research*, *45*(10), 1–16. https://doi.org/10.1029/2008WR007658

Boughton, W. (2015). Master recession analysis of transmission loss in some Australian streams. *Australian Journal of Water Resources*, *19*(1), 43–51. https://doi.org/10.7158/13241583.2015.11465455

Boussinesq, J. (1877). Essai sur la theories des eaux courantes. Memoires presentes par divers savants a l'Academic des Sciences de l'Institut National de France, Tome. In *1877* (XXIII).

Boussinesq, Joseph. (1877). *boussinesq1877essai : Essai sur la theorie des eaux courantes*. Impr. nationale.

Carlotto, T., & Chaffe, P. L. B. (2019). Computers and Geosciences Master Recession Curve Parameterization Tool (MRCPtool): Different approaches to recession curve analysis. *Computers and Geosciences*, *132*(February), 1–8. https://doi.org/10.1016/j.cageo.2019.06.016

Dewandel, B., Lachassagne, P., & Krishnamurthy, N. S. (2006). *A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering*. 260–284. https://doi.org/10.1016/j.jhydrol.2006.03.026

Endres, A. L., Jones, J. P., & Bertrand, E. A. (2007). Pumping-induced vadose zone drainage and storage in an unconfined aquifer: A comparison of analytical model predictions and field measurements. *Journal of Hydrology*, *335*(1–2), 207–218. https://doi.org/10.1016/j.jhydrol.2006.07.018

Fatchurohman, H., Adji, T. N., Haryono, E., & Wijayanti, P. (2018). Baseflow index assessment and master recession curve analysis for karst water management in Kakap Spring, Gunung Sewu. *IOP Conference Series: Earth and Environmental Science*, *148*(1). https://doi.org/10.1088/1755-1315/148/1/012029

Gregor, M. and Malík, P. (2012). *User manual for Recession Curve 4.0. Version 2*, 1–8.

Griffiths, G., & Clausen, B. (1997). Streamflow recession in basins with multiple water storages. *Journal of Hydrology*, *190*(1), 60–74.

Hammond, M., & Han, D. (2006). Recession curve estimation for storm event separations. *Journal of Hydrology*, *330*(3–4), 573–585. https://doi.org/10.1016/j.jhydrol.2006.04.027

Horton, R. (1933). The role of infiltration in the hydrological cycle. *Trans. Am. Geophys. Union*, *14*, 446–460.

Kovács, A. (2003). Geometry and hydraulic parameters of karst aquifers – A hydrodynamic modelling approach. In *PhD. thesis* (p. 131). La Faculté des sciences de l'Université de Neuchâtel, Suisse.

Kullman, E. (1990). Krasovo-puklinové vody. Karst-fissure waters. In *GÚDŠ, Bratislava, [in Slovak with Slovak Extended Sumarry]* (p. 184).

Latuamury, B., Marasabessy, H., Talaohu, M., & Imlabla, W. (2021). Small island watershed morphometric and hydrological characteristics in Ambon Region, Maluku Province. *IOP Conference Series: Earth and Environmental Science*, *800*(1). https://doi.org/10.1088/1755-1315/800/1/012047

Latuamury, B. O. (2018). Analisis Kurva Resesi Aliran Dasar Menggunakan Model Reservoir Linier Recession Curve Hydrooffice Pada Das Wuryantoro Kabupaten Wonogiri Propinsi Jawa Tengah. *Jurnal Teknosains*, *7*(1), 26. https://doi.org/10.22146/teknosains.32395

Latuamury, B., Parera, L. R., & Marasabessy, H. (2020). Characterizing river baseflow recession using linear reservoir model in Alang Watershed, Central Java, Indonesia. *Indonesian Journal of Geography*, *52*(1). https://doi.org/10.22146/ijg.43565

Latuamury, Bokiraiya, Imlabla, W., Sahusilawane, J., & Marasabessy, H. (2022). Comparing Master Recession Curve Shapes Between Linear and Exponential Reservoir Models. *Journal of Geographical Studies*, *6*(2), 68–72. https://doi.org/10.21523/gcj5.22060202

Latuamury, Bokiraiya, Osok, R. M., Puturuhu, F., & Imlabla, W. N. (2022). Baseflow separation using graphic method of recursive digital filter on Wae Batu Gajah Watershed, Ambon City, Maluku. *IOP Conference Series: Earth and Environmental Science*, *989*(1), 012028. https://doi.org/10.1088/1755-1315/989/1/012028

Lee, G., Shin, Y., & Jung, Y. (2014). Development of web-based RECESS model for estimating baseflow using SWAT. *Sustainability (Switzerland)*, *6*(4), 2357–2378. https://doi.org/10.3390/su6042357

Maillet, E. (1905). Essais d'Hydraulique Souterraine et Fluviale. In *Hermann Paris* (p. 218).

Nurkholis, A., Adji, T. N., Haryono, E., Cahyadi, A., Waskito, W. A., Fathoni, H., Kurniawan, I. A., & Agniy, R. F. (2019). Analysis of Master Recession Curve (MRC) and flood hydrograph components for karstification degree estimation in Kiskendo Cave, Jonggrangan Karst System, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *256*(1). https://doi.org/10.1088/1755-1315/256/1/012011

Rupp, D. E., & Selker, J. S. (2006). On the use of the Boussinesq equation for interpreting recession hydrographs from sloping aquifers. *Water Resources Research*, *42*(12), 1–15. https://doi.org/10.1029/2006WR005080

Şener, A., Yolcubal, İ., & Sanğu, E. (2020). Determination of recharge, storage and flow characteristics of a karst aquifer using multi-method approaches (Kocaeli, Turkey). *Hydrogeology Journal*, *28*(6), 2141–2157. https://doi.org/10.1007/s10040-020-02183-1

Stoelzle, M., Stahl, K., & Weiler, M. (2013). Are streamflow recession characteristics really characteristic? *Hydrology and Earth System Sciences*. https://doi.org/10.5194/hess-17-817-2013

Sujono, J., Shikasho, S., & Hiramatsu, K. (2004). A comparison of techniques for hydrograph recession analysis. *Hydrological Processes*, *18*(3), 403–413. https://doi.org/10.1002/hyp.1247

Tashie, A., Pavelsky, T., & Band, L. E. (2020). An Empirical Reevaluation of Streamflow Recession Analysis at the Continental Scale. *Water Resources Research*, *56*(1), 1–18. https://doi.org/10.1029/2019WR025448

Tashie, A., Pavelsky, T., & Emanuel, R. E. (2020). Spatial and Temporal Patterns in Baseflow Recession in the Continental United States. *Water Resources Research*, *56*(3), 1–18. https://doi.org/10.1029/2019WR026425