Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 12, No. 03, March, 2026

Discharge Estimation for Groundwater Basin Fully Delineated Watersheds Based on the Modified Rational Equation

Christine Mayavani [1, 2*], Indratmo Soekarno [1], Mohammad Farid [1], Ahmad Taufiq [2], Muhammad Farid Fakhruddin [2]

[1] *Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia.*

[2] *Center for Policy Implementation Analysis, General Secretariat, Ministry of Public Works, Jakarta, Indonesia.*

Received 06 November 2025; Revised 09 February 2026; Accepted 15 February 2026; Published 01 March 2026

Abstract

The integration of surface water and groundwater is essential for sustainable water resources management, as both components are hydrologically interconnected through runoff, interflow, and baseflow processes. Surface water and groundwater are inseparable components of the hydrological system, contributing significantly to streamflow and to the calculation of water availability in watersheds. A previous study proposed a simpler, improved equation based on a rational method to estimate potential discharge for fully delineated watersheds within a single groundwater basin. Therefore, this study aimed to analyze potential discharge by applying an equation from previous reports with the addition of a beta (β) parameter to enhance performance. The modified rational equation was compared with three existing methods, namely FJ Mock, Sacramento, and NRECA, across six selected watersheds, including Cidanau, Kupang, Kuto, Sampean, Belawan, and Kumai. The results showed that the modified rational equation achieved the highest correlation coefficient and very good RSR classification, except for Kuto and Belawan. This showed that incorporating the β parameter as a baseflow correction factor in the Modified Rational Equation enhanced model accuracy, as indicated by higher correlation and lower RSR values. Optimal β values showed a strong relationship with watersheds-to-groundwater basin area ratio (A_{WS}/A_{GWB}), determined through an iterative process. The modified rational equation performed optimally in small watersheds (<250 km²), with correlation values >60% in catchments like Cidanau, Kupang, and Kuto. However, the accuracy decreased in larger areas, suggesting suitability for small-scale hydrological systems. The enhancement of the modified rational equation using the β parameter showed an alternative method for determining water availability and potential to improve the development of strategic frameworks of water resource management in Indonesia.

Keywords: Modified Rational Equation; Watersheds; Groundwater Basin.

1. Introduction

The Integrated Water Resources Management (IWRM) method is a framework that enables a comprehensive understanding of the interconnections between surface water and groundwater, thereby enhancing the effectiveness, sustainability, and adaptive capacity of hydrological governance [1, 2]. This method promotes adaptive and resilient strategies that enable decision-makers to address complex hydrological challenges through coordinated policy and planning efforts [3, 4]. In support of the IWRM framework, the water balance concept should be emphasized as a fundamental analytical tool to quantify hydrological components such as precipitation, runoff, evapotranspiration, and changes in surface and subsurface storage [5, 6].

* Corresponding author: mayavanie2@gmail.com; christine.mayavani@pu.go.id

https://doi.org/10.28991/CEJ-2026-012-03-04

Regarding water balance in watersheds, accurate assessment of water availability requires a detailed understanding of streamflow components, including runoff, interflow, and baseflow [7, 8]. Generally, surface runoff occurs when rainfall intensity exceeds the soil's infiltration capacity, resulting in excess water flowing over the land surface [9]. When the infiltration capacity is reached, excess water can flow into the subsurface (interflow) and percolate downward through the soil profile toward the saturated zone (baseflow) [10]. Interflow refers to the lateral movement of water through the unsaturated subsurface layer, and flow contributes to stream discharge, particularly at lower elevations [11]. Baseflow is the sustained groundwater contribution to the river and a key indicator of long-term water availability, particularly during dry periods [12]. Given the significant role of baseflow in sustaining the surface water system, watershed management strategies must adopt an integrated approach that explicitly accounts for groundwater basin conditions [13].

Several hydrologic models are commonly used to estimate water availability in watersheds, such as FJ Mock, Sacramento, and NRECA. In Indonesia, FJ Mock and NRECA methods are widely used in watershed modeling and water-balance calculations. NRECA performs better in capturing daily fluctuations, while FJ Mock is more stable for monthly estimations [14]. FJ Mock has shown superior performance in simulating average monthly discharge, while NRECA is more responsive to extreme rainfall events [15]. The Sacramento model offers a more comprehensive depiction of soil parameters in modulating soil storage capacity on surface water flow [16, 17]. Compared to other models, the FJ Mock and NRECA methods are relatively simple rainfall–runoff models that primarily depend on runoff and baseflow parameters for streamflow estimation. [18, 19]. The Sacramento model adopts a more comprehensive method by explicitly accounting for runoff, interflow, and baseflow components [20]. This model shows superior performance in representing subsurface hydrological processes (soil water and groundwater), but requires more detailed input data, including both major and minor parameters [16].

Building on the critical role of runoff, interflow, and baseflow in sustaining watersheds' hydrology, the use of hydrologic models is essential to adequately represent these components using simpler equations, fewer variables, and minimal assumptions. Therefore, this study introduces a streamlined equation for estimating water availability in a fully delineated watershed within a single groundwater basin. The proposed equation adapts the rational equation by emphasizing interflow and baseflow parameters, which are influenced by aquifer potential within the groundwater basin. The rational equation and modified forms are used to estimate peak discharge and design flows in small-scale watersheds [21, 22]. However, the application of the Rational and Modified Rational Method has remained limited to preliminary assessments of water balance, creating the opportunity to further modify and test the equation for estimating water availability by integrating both surface water and groundwater processes. Therefore, this study aims to assess potential discharge and dependable flow for water availability in fully delineated watersheds within a single groundwater basin by applying the modified rational equation from previous reports [23], with the addition of the beta (β) parameter as a modification. The modified equation is compared with results from established hydrological models, namely FJ Mock, NRECA, and Sacramento, to assess accuracy and suitability for watershed management applications. The results are expected to provide valuable information on the modified rational equation, serving as a foundational framework to support strategic water resource management in Indonesia.

This paper is structured as follows. Section 2 describes the study area, data sources, and methodological framework, including the development of the Modified Rational Equation and its enhancement using the β parameter. Section 3 presents results and discussion, covering potential discharge analysis, comparative analysis with established hydrological models, and performance assessment of the enhanced equation. Finally, Section 4 summarizes the conclusions or main findings, highlights the applicability of the modified rational equation, and outlines recommendations for future research and water resources management.

2. Material and Methods

2.1. Study Area

According to the Regulation of the Minister of Public Works and Housing (PUPR) for Indonesia Number 04/PRT/M/2015 Concerning Criteria and Designation of River Regions [24], river basin territories are delineated into 128 units comprising 7,977 watersheds. Considering the widespread distribution, this study used six selected watersheds, including Cidanau, Kupang, Kuto, Belawan, Sampean, and Kumai, for analytical calculations [25]. The selection was performed to demonstrate the effectiveness of the Modified Rational Equation method in small (<250 km²) and moderate watersheds (250–2,500 km²), assuming that all fully delineated watersheds are located within a single groundwater basin. The delineation and governance of groundwater basins are legally established through the Regulation of the Minister of Energy and Mineral Resources (ESDM) for Indonesia Number 2 Year 2017 Concerning Groundwater Basins. Based on this regulation [26], the land area totaling approximately 1,922,600 km² is categorized into 421 groundwater basins covering 47.2% of the territory (907,615 km²), while the remaining 52.8% (1,014,985 km²) is considered non-potential [27]. The delineation of watersheds and groundwater basin boundaries follows the regulatory framework established by the Indonesian government, as shown in Figure 1 and Table 1.

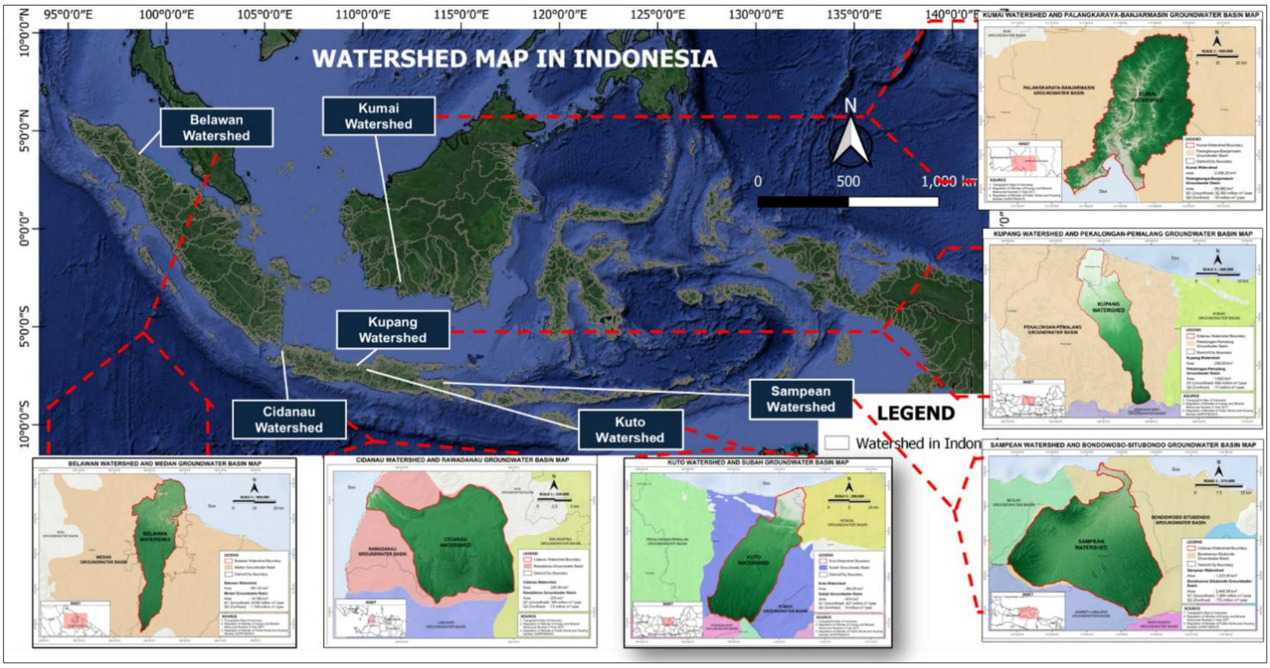


Figure 1. Distribution of Selected Watersheds Map (Cidanau, Kupang, Kuto, Sampean, Belawan, and Kumai)

Table 1. Study Area of Selected Watersheds

No.	Watersheds (WS)	Area of WS (km²)	Watersheds Length (km)	Watersheds Width (km)	Groundwater Basin (GWB)	Area of GWB (km²)	Location
1	Cidanau	226.06	24.32	9.30	Rawadanau	375.00	Serang and Pandeglang, Banten Province.
2	Kupang	235.63	37.48	6.85	Pekalongan-Pemalang	1,682.00	Pekalongan city and Pekalongan regency, Central Java Province.
3	Kuto	364.28	35.41	9.78	Subah	874.00	Batang Regency and Kendal Regency, within Central Java Province
4	Sampean	1,223.93	50.35	24.31	Bondowoso – Situbondo	2,446.58	Situbondo, Bondowoso, and Jember, within East Java Province
5	Belawan	957.53	72.78	13.16	Medan	19,786.00	Medan, Deli Serdang, and Binjai, within North Sumatra.
6	Kumai	2,456.29	66.03	37.20	Palangkaraya-Banjarmasin	95,980.00	West Kotawaringin, Central Kalimantan Province

2.2. Data Parameter

The analysis of potential discharge in watersheds delineated by a groundwater basin was influenced by hydrometeorological, land-use, groundwater-potential discharge (unconfined and confined), soil permeability, and river-discharge observations. The use of analytical parameter data on potential discharge in watersheds is shown in Table 2.

Table 2. Data Parameter

No.	Data Parameter	Type of Data	Source
1	Hydrometeorological Data	a) Cidanau Watershed: 20 years hydrometeorological time series data (2001 - 2020)	a) Serang Climatology Station
		b) Kupang Watershed: 20 years hydrometeorological time series data (2003 - 2022)	b) Tegal Climatology Station
		c) Kuto Watershed: 20 years hydrometeorological time series data (2003 - 2022)	c) Kertosari Rainfall Station and Kebaturan Climatology Station
		d) Sampean Watershed: 20 years hydrometeorological time series data (2003 - 2022)	d) Sukokerto Rainfall Station and Kebaturan Bondowoso Station
		e) Belawan Watershed: 20 years hydrometeorological time series data (2003 - 2022)	e) Deli Serdang Climatology Station
		f) Kumai Watershed: 20 years hydrometeorological time series data (2003 - 2022)	f) Iskandar Climatology Station

2	Observed River Discharge Data	a) Cidanau Watershed: 12 years of observed streamflow time series data (2001 - 2012) b) Kupang Watershed: 17 years of observed streamflow time series data (2003 - 2019) c) Kuto Watershed: 6 years of observed streamflow time series data (2008 - 2013) d) Sampean Watershed: 6 years of observed streamflow time series data (2010 - 2015) e) Belawan Watershed: 5 years of observed streamflow time series data (2009 - 2013) f) Kumai Watershed: 5 years of observed streamflow time series data (2009 - 2013)	a) Water Gauge Station in Peusar Village b) Water Gauge Station in Kupang-Kuripan Kidul c) Water Gauge Station in Kuto-Kutosari d) Water Gauge Station in Tenggarang - Sampean e) Water Gauge Station in Sei Belawan-Asam Kumbang f) Water Gauge Station in Kumai-Tempenik
3	Land Use Data	Distribution of land use in 2022	Geospatial Information Agency (BIG)
4	Soil Data	Soil permeability (k)	FAO's Harmonized World Soil Database (HWSD) version 2.0
5	Groundwater Potential Data	Area of GWB and Aquifer Potential Discharge (Unconfined and Confined)	Regulation of Minister of Energy and Mineral Resources (ESDM) for Indonesia Number 2 Year 2017 Concerning Groundwater Basin

This study used data from credible Indonesian government institutions to provide information. Hydrometeorological data, including rainfall and evapotranspiration, play an essential role in assessing potential discharge, given their significant influence on water availability within a region. Based on common practice in hydrological and climatological studies, a rainfall record of 20–30 years is generally considered sufficient to represent medium-term climate variability and annual rainfall patterns. Several studies published in the last five years reported that hydrological analyses, including extreme rainfall estimation, water balance assessment, and rainfall runoff modeling, could be reliably conducted using data spanning 16–30 years [28, 29].

For the analysis, the observed river discharge data were obtained from daily recordings collected by the Automatic Water Level Recorder (AWLR) installed at gauging stations across all watersheds. These data served as calibration parameters for validating the outputs of hydrological model simulations. Temporal variations in the observed data among watersheds were primarily attributed to differences in the availability and continuity of field-recorded hydrological measurements. Moreover, the selection of the observation period was based on the availability of historical monthly discharge records, ensuring that the dataset adhered to established quality standards.

Land use data were applied to calculate the direct runoff coefficient (c) within a watershed, based on Indonesian National Standard (SNI) 2415:2016, Concerning Flood Discharge Measurement Methods [30]. The runoff coefficient (c) quantified the fraction of precipitation contributing to surface runoff and was influenced by factors such as soil characteristics, vegetation density, topography, and land use patterns. This parameter plays a critical role in accurately estimating river discharge throughout the year. An increase in impervious land cover leads to a corresponding rise in runoff volumes, which can reduce groundwater recharge and negatively affect surface water quality [31].

Soil permeability data were obtained from the FAO Harmonized World Soil Database (HWSD) version 2.0. This parameter describes the ability of soil to allow water to move through pore spaces, based on pore size, arrangement, distribution, texture, and structural composition. Furthermore, it plays a vital role in determining how quickly rainfall infiltrates the ground and contributes to groundwater recharge. Soil permeability data are used to calculate the interflow coefficient, which refers to the lateral movement of water within the soil above a saturated zone and discharging into a river or other water body at a lower elevation than the origin. This type of flow is described as semi-deep, located above the baseflow region [25].

Groundwater potential data are essential for calculating the baseflow coefficient (b). Baseflow represents the sustained flow of water into rivers during dry periods, which is primarily sourced from groundwater. It is also a significant indicator of low-flow conditions, serving as an essential component in assessing water availability during droughts [32]. Groundwater potential data include both unconfined and confined aquifer potentials, as defined by Indonesian government regulations, as shown in Table 3.

Table 3. Groundwater potential data based on unconfined and confined aquifers

No.	Watersheds (WS)	Groundwater Basin (GWB)	Area of GWB (km^2)	Aquifer Potential Data
1	Cidanau	Rawadanau	375.00	Unconfined: 180 million m^3/year; and Confined: 13 million m^3/year
2	Kupang	Pekalongan-Pemalang	1,682.00	Unconfined: 644 million m^3/year; and Confined: 17 million m^3/year
3	Kuto	Subah	874.00	Unconfined: 427 million m^3/year; and Confined: 8 million m^3/year
4	Sampean	Bondowoso-Situbondo	2,446.58	Unconfined: 1,426 million m^3/year; and Confined: 172 million m3/year
5	Belawan	Medan	19,786.00	Unconfined: 6,040 million m3/year; and Confined: 1,109 million m^3/year
6	Kumai	Palangkaraya-Banjarmasin	95,980.00	Unconfined: 32,393 million m^3/year; and Confined: 16 million m^3/year

2.3. Method

The theoretical method underlying the development of the monthly potential discharge formula originated from the need to bridge the gap among simple hydrologic models such as FJ Mock, NRECA, and Sacramento. Generally, FJ Mock and NRECA incorporate only runoff and baseflow components, showing less efficiency in representing subsurface flow dynamics that play a crucial role in sustaining continuous streamflow [18, 19]. In comparison, Sacramento includes runoff, interflow, and baseflow, enabling a more realistic representation of surface and subsurface hydrological processes, though it requires complex parameters and detailed input data [20]. Given the importance of the three components in maintaining watershed hydrology, this study proposes a theoretical method that simplifies the representation of runoff, interflow, and baseflow by modifying the rational equation to estimate peak discharge in small watersheds [21, 22] . The modified rational equation is adapted to capture monthly water availability by incorporating interflow (i) and baseflow (b) parameters influenced by soil permeability and aquifer potential in fully delineated watersheds within a single groundwater basin, as shown in Figure 2.

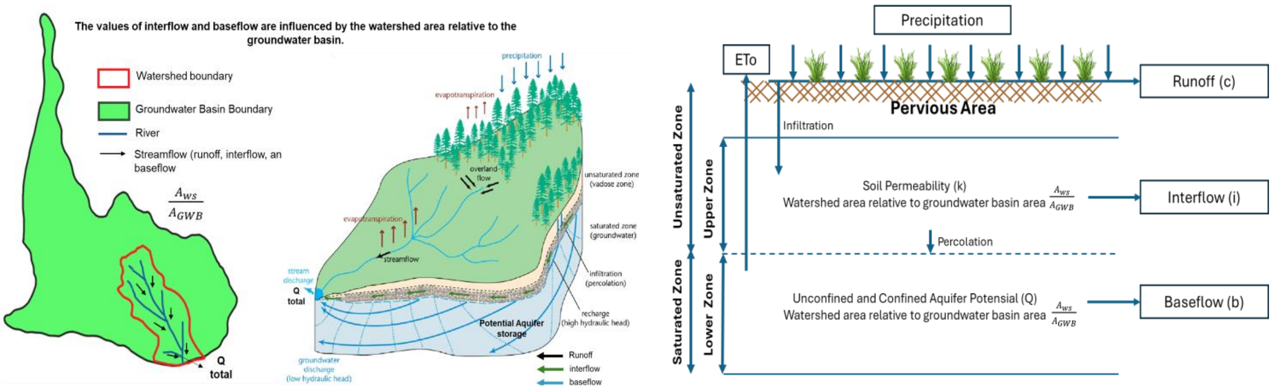


Figure 2. Illustration of the method for determining the modified rational equation in streamflow runoff, interflow, and baseflow, modified from [33]

In the framework (Figure 3), runoff is the portion of rainfall that does not infiltrate the soil surface and flows directly into river channels. Interflow describes the lateral subsurface flow (soil water) that moves through the soil layer. This component is characterized by soil permeability (k), showing the subsurface hydrological response within the fully delineated watershed–groundwater basin system (A_{WS}/A_{GWB}). Meanwhile, baseflow denotes the contribution of groundwater discharge originating from the aquifer potential within the groundwater basin, providing a continuous flow component to the river system. The potential discharge of water availability can be estimated using the modified rational equation, considering the influence of groundwater flow and interactions with the surrounding aquifer system in fully delineated watersheds within a single groundwater basin. This modified rational equation is expressed as follows:

From Rational Equation:

$$Q = C.I.A \tag{1}$$

To Modified Rational Equation for Potential Discharge:

$$Q = \{(1 - c) + b + i\} \times (P - E_a) \times A_{ws} \tag{2}$$

Since (P-Ea) is in mm/month and A_{WS} is in km^2, converting it into the correct unit m^3/s is essential. If the equation is completed with the conversion value, then it becomes:

$$Q = \{(1 - c) + b + i\} \times (P - E_a) \times A_{ws} \times \frac{1000}{n \times 24 \times 3600} \tag{3}$$

where, Q is discharge (m^3/s), c is runoff coefficient, b is baseflow coefficient, i is interflow coefficient, P is precipitation (mm/month), Ea is Evapotranspiration (mm/month), A_{WS} is area of the watersheds (m^2), and n is the number of days in a month. Moreover, the coefficient of baseflow and interflow are dimensionless, defined as follows:

$$b = \frac{1}{P} \times \left(\frac{A_{WS} \times (Q_{unconfined} + Q_{confined})}{A_{GWB}{}^2} \right) \times 1000 \tag{4}$$

In this equation, b =baseflow coefficient is non-dimensional, $Q_{unconfined}$ is potential discharge of unconfined aquifer (m^3/month), $Q_{confined}$ is potential discharge of confined aquifers (m^3/month), A_{GWB} is area of groundwater basin (m^2), and A_{ws} is area of watersheds (m^2).

$$i = \frac{1}{P} \times \left(k \times \frac{A_{WS}}{A_{GWB}} \times n \right) \times 1000 \quad (5)$$

In this equation, i =interflow coefficient is non-dimensional, k is soil permeability (m/s), n is the number of days in a month (day), and A_{ws} is the area of watersheds (m^2).

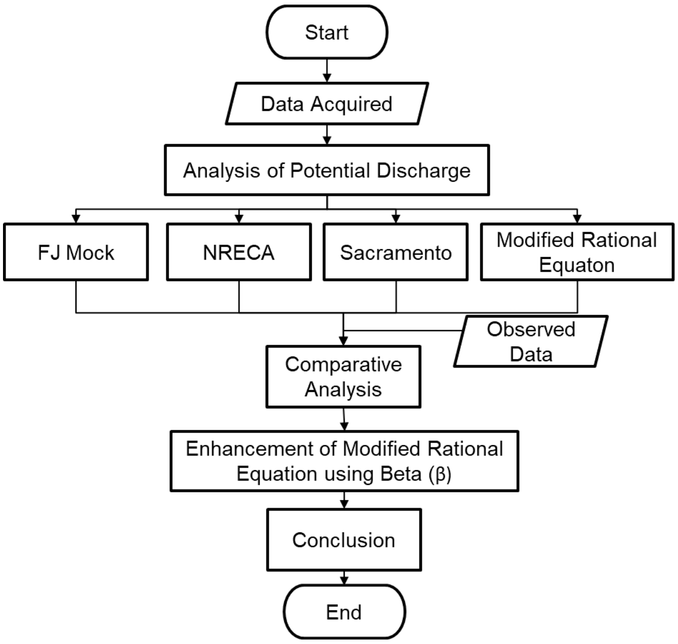


Figure 3. Study Framework Flowchart

In the next phase, the results obtained from the modified rational equation would be compared with three conventional methods commonly used in water availability analysis in Indonesia, namely FJ Mock, NRECA, and Sacramento. The objective of this comparison is to evaluate the performance of the modified rational equation in estimating potential discharge and reliable flow values for fully delineated watersheds within a single groundwater basin. This process includes model calibration and verification using correlation analysis and the RSR coefficient to assess the degree of agreement between simulation results and observed data. A comparison of the parameter types and the number of parameters used in this study is summarised in Table 4.

Table 4. Parameter of Each Method

No.	FJ Mock	NRECA	Sacramento	Modified Rational Equation
1	Catchment area	Catchment area	Catchment area	Catchment area
2	Monthly precipitation (R)	Monthly precipitation (R)	Monthly precipitation (R)	Monthly precipitation (R)
3	Evapotranspiration Potential (ETo)	Evapotranspiration Potential (ETo)	Evapotranspiration Potential (ETo)	Evapotranspiration Potential (ETo)
4	Soil Moisture Capacity	Initial moisture capacity	UZTWM	Groundwater basin area (A_{GWB})
5	Infiltration coefficient (i)	Annual precipitation	UZFWM	Groundwater potential data →(b)
6	Coefficient of recession (K)	Topsoil permeability	LZTWM	Soil Permeability (k)→ i
7	Days of rain (n)	Subsoil permeability	LZFSM	Runoff coefficient (c)
8	Exposed surface (m)	Coefficient of reduction	LZFPM	
9			UZK	
10			LZSK	
11			LZPK	
12			ZPERC	
13			REXP	
14			PFREE	
15			RSERV	
16			PCTIM	
Number of Parameters	**8**	**8**	**16**	**7**

The flowchart in Figure 3 shows the study framework that is systematically conducted in line with the procedural methods. The process began with problem identification and preliminary data collection, followed by data analysis to clarify the study objective. Subsequently, an appropriate problem-solving method was designed and further tested through calibration and validation. The outcomes were evaluated to assess effectiveness, success rate, and potential limitations. The entire sequence of processes in the flowchart led to the formulation of conclusions and recommendations, which served as the main outputs of this study in developing the modified rational equation for discharge estimation.

3. Results and Discussion

3.1. Potential Discharge Analysis

Based on the results of FJ Mock model calculations, the average annual discharge over a 20-year data series was obtained for each watershed. These included Cidanau (5.74 m^3/s), Kupang (3.64 m^3/s), Kuto (13.09 m^3/s), Sampean (26.21 m^3/s), Belawan (21.27 m^3/s), and Kumai (95.75 m^3/s). The results of Sacramento model calculations showed an average annual discharge over a 20-year data series for Cidanau (7.29 m^3/s), Kupang (7.56 m^3/s), Kuto (16.10 m^3/s), Sampean (61.79 m^3/s), Belawan (36.78 m^3/s), and Kumai (124.19 m^3/s). However, NRECA model separated water storage into two components, namely moisture and groundwater. Surplus water from the moisture storage contributed to direct runoff or groundwater recharge. Groundwater flow (baseflow) was estimated from the volume stored in the groundwater reservoir. The primary input parameters for this model were rainfall, climatological data, and land use coefficients. Based on the calculation results, the average annual discharge over a 20-year data series was obtained for each watershed, namely Cidanau (4.93 m^3/s), Kupang (7.23 m^3/s), Kuto (4.06 m^3/s), Sampean (6.18 m^3/s), Belawan (15.04 m^3/s), and Kumai (60.40 m^3/s).

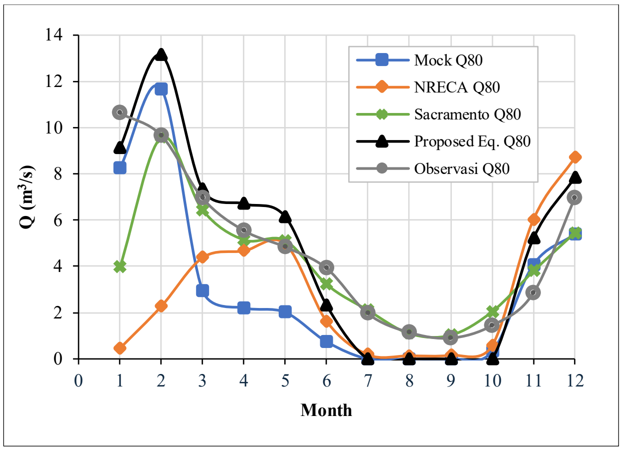
Runoff coefficient (c) for all selected watersheds was determined through an overlay process using the land use map in 2022 provided by the Geospatial Information Agency, conducted in QGIS 3.28.2. Prior to assigning runoff coefficients, the original land-use dataset obtained from the Geospatial Information Agency (BIG) was reclassified to ensure consistency with land-use categories defined in SNI 2415:2016. Several detailed land-cover classes were aggregated into broader categories, such as built-up/developed area, agricultural land, forest, and water bodies, following the standard classification scheme of the SNI.The values of c were assigned based on SNI 2415:2016, the Indonesian National Standard for Flood Discharge Measurement Methods [30], as presented in Table 4. Soil permeability value (k) for six selected watersheds was obtained through an overlay analysis using data from FAO's Harmonized World Soil Database (HWSD) version 2.0, conducted in QGIS version 3.28.2, as presented in Table 5. Subsequently, the k values were used in Equation 5 to calculate the interflow coefficient (i). The baseflow coefficient (b) was derived from groundwater potential discharge data through the application of Equation 4, as presented in Table 5.

Table 5. Runoff coefficient (c) and Soil Permeability (m/s) of six selected watersheds

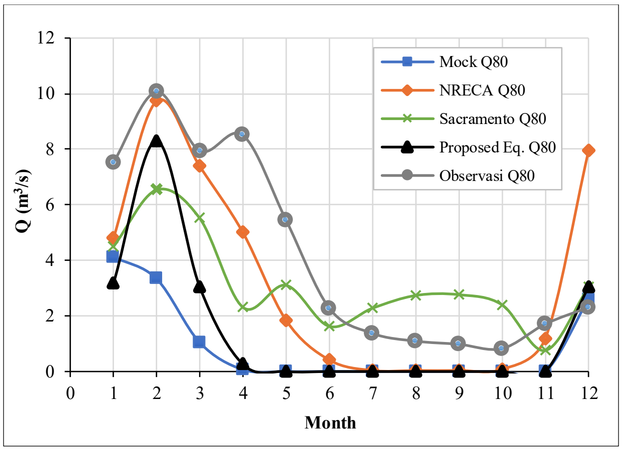
No.	Watersheds (WS)	Area of WS (km^2)	Runoff Coefficient (c)	Soil Permeability (m/s)
1	Cidanau	226.06	0.462	9.36×10^{-6}
2	Kupang	235.63	0.335	4.19×10^{-6}
3	Kuto	364.28	0.439	3.83×10^{-6}
4	Sampean	1,223.93	0.404	3.93×10^{-7}
5	Belawan	957.53	0.431	4.18×10^{-7}
6	Kumai	2,456.29	0.414	9.59×10^{-7}

The results of Modified Rational Equation model calculations using Equation 1 showed the average annual discharge over a 20-year data series for each watershed, including Cidanau (7.68 m^3/s), Kupang (5.28 m^3/s), Kuto (11.43 m^3/s), Sampean (39.24 m^3/s), Belawan (39.54 m^3/s), and Kumai (89.36 m^3/s). By comparing the results, Sacramento method produced the highest average annual discharge over a 20-year data series for all watersheds. For Kupang, the highest average discharge was obtained using NRECA method, while the Modified Rational Equation obtained the largest discharge for Belawan watershed.

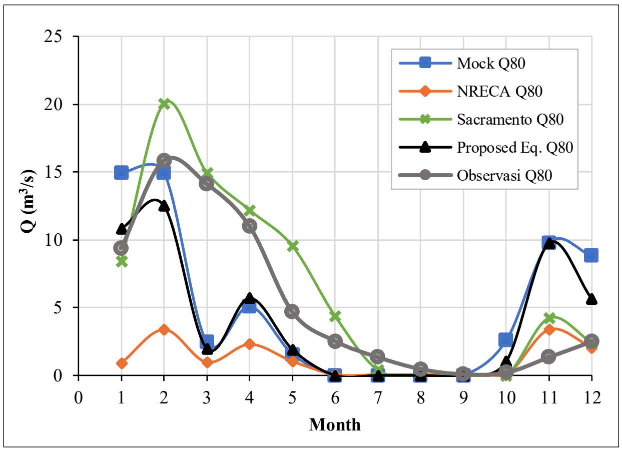
In hydrological analysis, dependable flow/discharge refers to the quantifiable streamflow available within a specified probability over a given period. The 80% dependable discharge (Q80) denotes the flow magnitude that is equalled or exceeded in 80% of the time during the observation period. To estimate Q80, monthly streamflow records were statistically processed by ranking discharge values in descending order. The probability of exceedance for each value was calculated using the Weibull distribution. The calculated Q80 values from the FJ Mock, Sacramento, NRECA, and Modified Rational Equation models are presented and systematically compared with the observed Q80 discharge derived from AWLR data across the six selected watersheds, as shown in Figure 4.



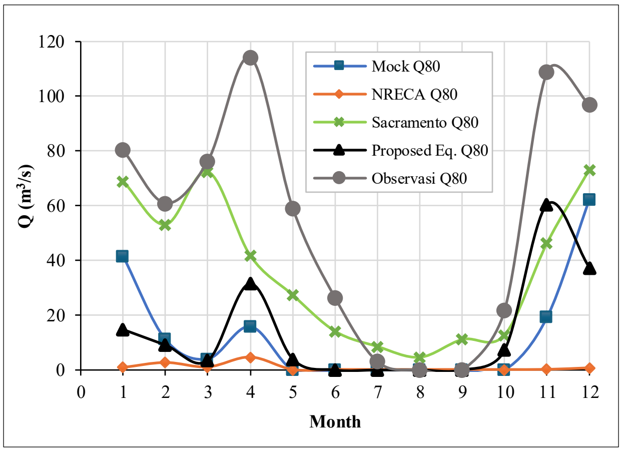
(a) Q80 of Cidanau Watershed



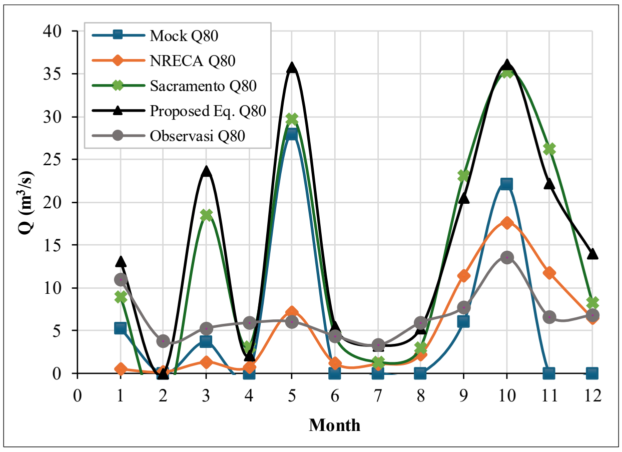
(b) Q80 of Kupang Watershed



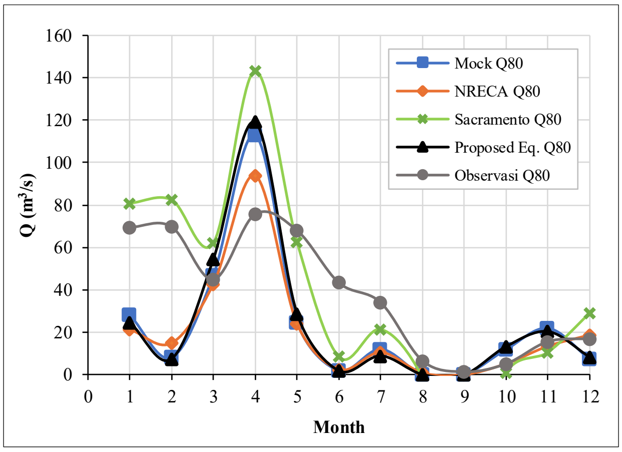
(c) Q80 of Kuto Watershed



(d) Q80 of Sampean Watershed



(e) Q80 of Belawan Watershed



(f) Kumai Watershed (2009 – 2013)

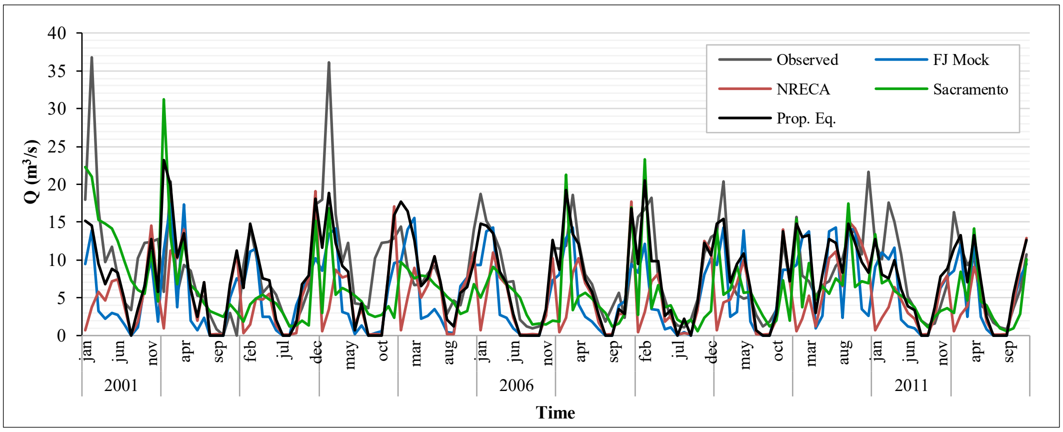
Figure 4. Graphical representation of the comparative analysis between model-simulated Q80 discharge values (FJ Mock, Sacramento, NRECA, and Modified Rational Equation) and observed Q80 discharge data across selected watersheds

3.2. Comparative Analysis

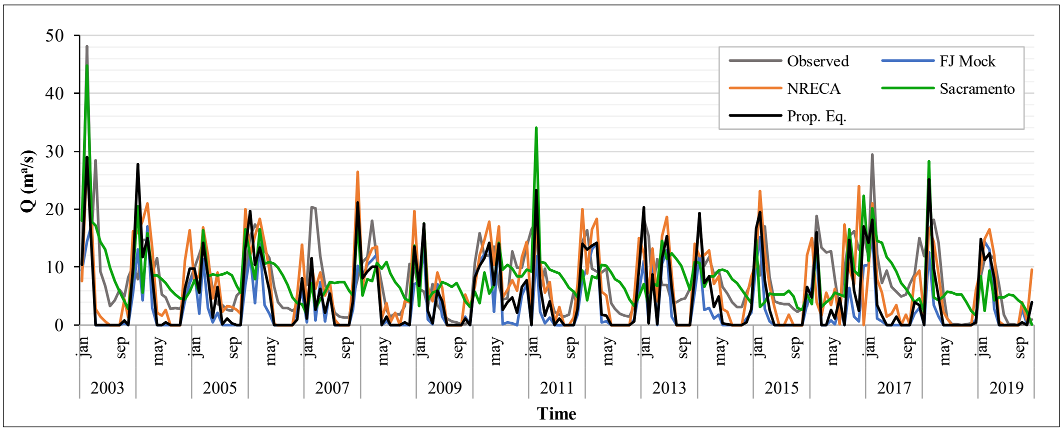
The primary objective of comparing hydrological models is to evaluate the performance and reliability of each model in representing watershed processes. This comparative analysis aims to identify the model that best correlates with the specific hydrological and physical characteristics of watersheds. The outcomes are expected to provide valuable insight into model selection in various applications such as water balance analysis and water resources management within diverse watersheds. To identify the most reliable method for estimating potential discharge, a comparative analysis was conducted using observed river discharge data (AWLR) from all selected watersheds. A total of four hydrological models, including F.J. Mock, Sacramento, NRECA, and the Modified Rational Equation, were evaluated, as shown in Table 6 and Figure 5.

Table 6. Comparative analysis of four model hydrology to observed data

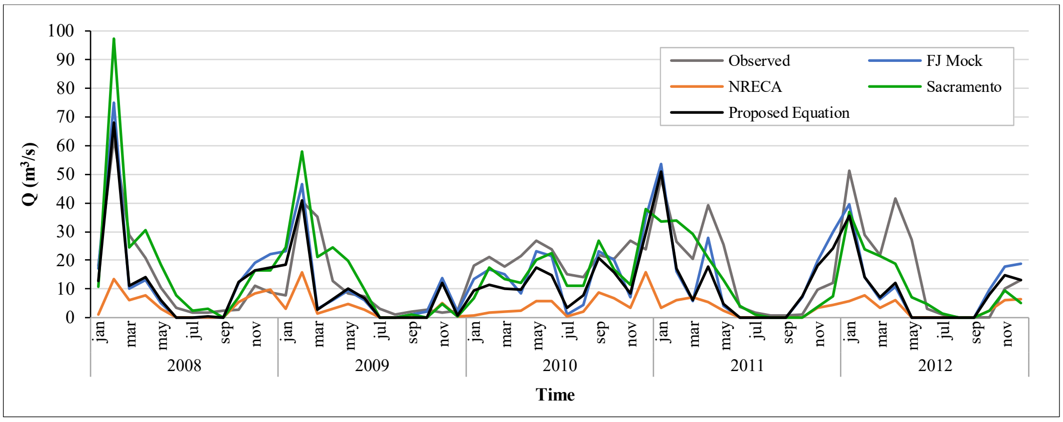
No.	Watersheds	A_{ws} (km^2)	Methods	Calibration	
				Correlation	RSR
1.	Cidanau	226.06	FJ. Mock	61.87%	0.079
			Sacramento	51.15%	0.082
			NRECA	32.13%	0.100
			Modified Rational Eq.	70.21%	0.063
2.	Kupang	235.63	FJ. Mock	54.19%	0.079
			Sacramento	52.88%	0.076
			NRECA	60.14%	0.066
			Modified Rational Eq.	63.07%	0.082
3.	Kuto	364.28	FJ. Mock	64.13%	0.102
			Sacramento	78.63%	0.079
			NRECA	48.65%	0.136
			Modified Rational Eq.	67.13%	0.094
4.	Sampean	1223.93	FJ. Mock	48.38%	0.165
			Sacramento	57.94%	0.124
			NRECA	43.07%	0.197
			Modified Rational Eq.	58.08%	0.142
5.	Belawan	957.53	FJ. Mock	41.94%	0.77
			Sacramento	46.30%	1.16
			NRECA	47.40%	0.37
			Modified Rational Eq.	47.47%	1.11
6.	Kumai	2456.29	FJ. Mock	37.38%	0.199
			Sacramento	35.81%	0.205
			NRECA	35.13%	0.178
			Modified Rational Eq.	41.24%	0.162



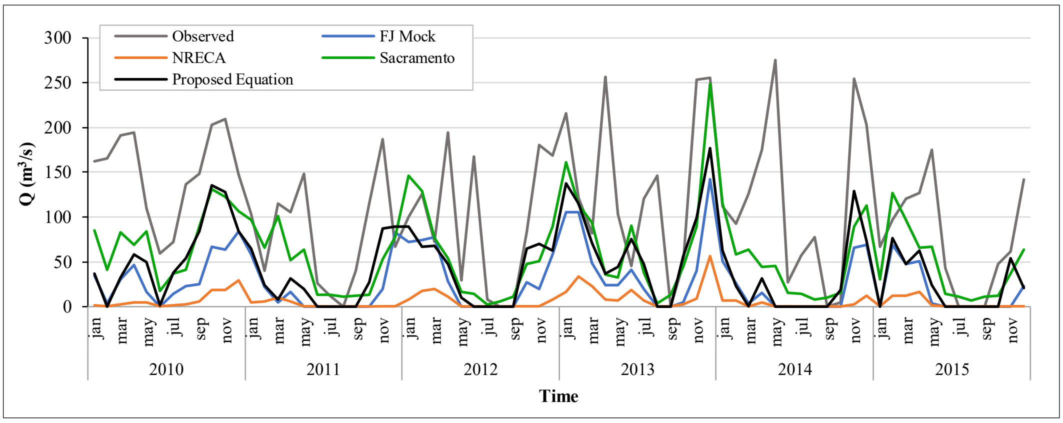
(a) Cidanau Watershed (2001–2012)



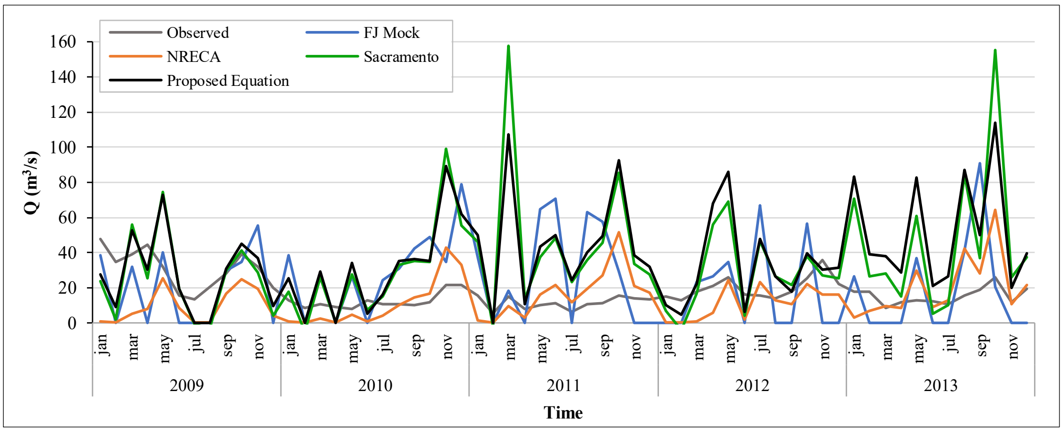
(b) Kupang Watershed (2003–2019)



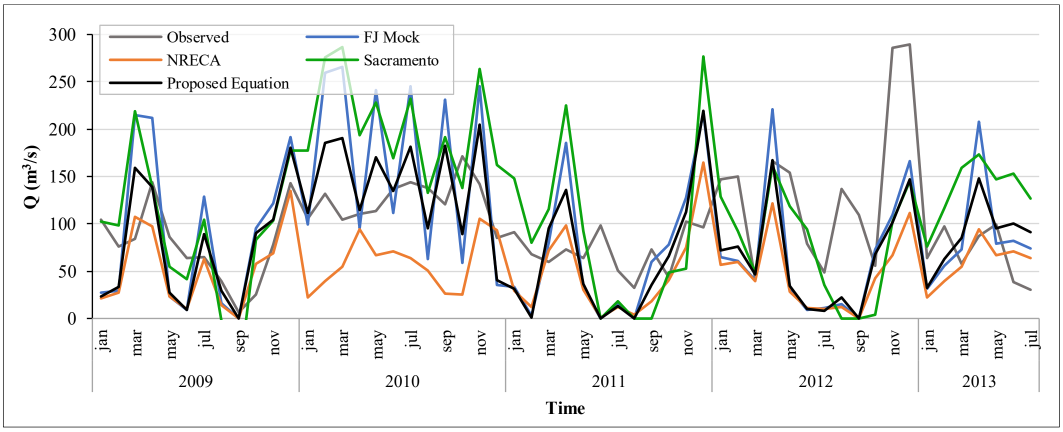
(c) Kuto Watershed (2008–2013)



(d) Sampean Watershed (2010–2015)



(e) Belawan Watershed (2009–2013)



(f) Kumai Watershed (2009–2013)

Figure 5. Graphical representation of the comparative analysis between Q calculation (FJ Mock, Sacramento, NRECA, and Modified Rational Equation) and Q observation across selected watersheds

The comparative analysis between simulated discharge and observed data showed that the Modified Rational Equation outperformed the other three hydrological models in terms of correlation strength across Cidanau (70.21%), Kupang (63.07%), Sampean (58.08%), Belawan (47.47%), and Kumai (41.24%). These results show a higher degree of statistical correlation and model robustness in representing catchment hydrological responses. In comparison, the Sacramento model showed the highest correlation coefficient in Kuto (78.63%), suggesting greater suitability under the specific hydrometeorological and physical conditions. The comparative analysis showed that medium-sized watersheds had lower correlation coefficients relative to smaller catchments (A_{ws} < 500 km²), such as Cidanau, Kupang, and Kuto. This trend suggests that the Modified Rational Equation shows enhanced performance and predictive reliability within small watersheds [34, 35]. However, the preliminary indication requires further investigation to comprehensively evaluate the influence of watershed scale on model sensitivity and hydrological response accuracy [36].

The lowest RSR values were observed in the Modified Rational Equation method for Cidanau (0.063), Sampean (0.142), and Kumai (0.162) watersheds. In comparison, the lowest RSR value for Kupang (0.066) was obtained using the NRECA model, while the Sacramento model produced the least for Kuto (0.079). These results show the spatial variability in model performance across different catchments, indicating the influence of watersheds-specific hydrological and physical conditions on the effectiveness of rainfall-runoff simulation models. Application of four hydrological models across the five selected watersheds produced RSR values within the range of 0.00 ≤ RSR ≤ 0.50, which corresponded to a 'very good' model performance classification [37, 38]. However, Belawan showed poor model performance, as indicated by high RSR values generated using FJ Mock (0.77), Sacramento (1.16), and Modified Rational Equation (1.11). The values fall within the range > 0.70, which corresponds to an 'unsatisfactory' model performance classification. This shows the need for further investigation regarding the reliability of the observed discharge data and emphasizes the need for higher-quality observational datasets to improve model accuracy [39].

3.3. Enhancement of Modified Rational Equation

The enhancement of the modified rational equation through the inclusion of the β parameter aims to improve the estimation of potential discharge, considering the influence of the groundwater basin on hydrological processes. This modification refines the previously developed modified rational equation [40] by introducing a correction factor, β that adjusts for the variability in baseflow contributions relative to watersheds. The β parameter serves as a coefficient that represents the relationship between the capacity of watersheds and the groundwater basin to support baseflow. By incorporating this parameter, the equation accounts for spatial variations in rainfall infiltration, baseflow, and subsurface water dynamics across the entire watersheds. The method enables a more accurate representation of interactions between surface and subsurface water processes, thereby improving the model's ability to estimate water availability. The modified rational equation with the addition of β parameter based on Equation 2 is expressed as follows.

$$Q = \{(1 - c) + b^{\beta} + i\} \times (P - Eo) \times A_{ws} \tag{6}$$

where, β is correction factor of baseflow (non-dimensional).

The modified rational equation was calculated using Equation 6, incorporating beta (β) as a correction factor. Specifically, this factor represents the hydrological interaction between groundwater and surface water in a condition where a single watershed is entirely within a fully delineated groundwater basin, enabling a more accurate correction of the baseflow component. The value of β is determined through two methods, namely an iterative trial-and-error and the application relationship of the groundwater basin as well as watersheds using Equation 7.

$$\beta = \frac{A_{WS}}{A_{GWB}} \tag{7}$$

where, A_{GWB} is the area of the groundwater basin, and A_{WS} is the area of the watersheds.

Based on Equation 6, calculations were carried out to determine the ratio of the watershed area to the groundwater basin area, as shown in Table 7.

Table 7. Ratio Value (A_{WS}/A_{GWB}) in six selected watersheds

No.	Watersheds	A_{WS} (m²)	A_{GWB} (m²)	Ratio (A_{WS}/A_{GWB})
1	Kumai	2456.29	95980.00	0.026
2	Belawan	957.53	19786.00	0.048
3	Kupang	235.63	1682.00	0.140
4	Kuto	364.28	874.00	0.417
5	Sampean	1223.93	2446.58	0.500
6	Cidanau	226.06	375.00	0.603

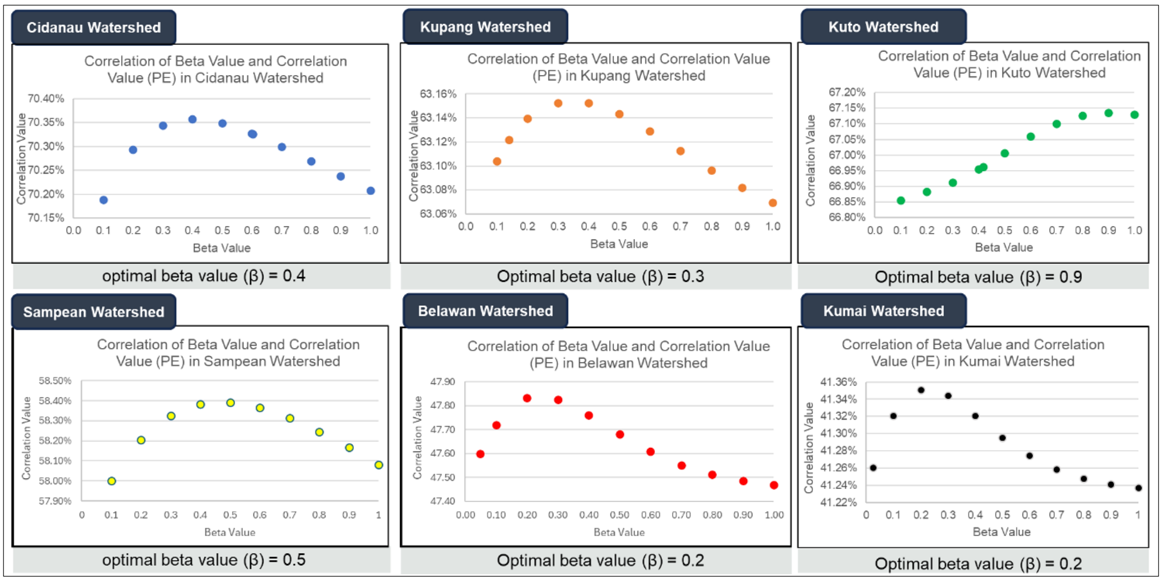


Figure 6. The influence of iterative β value on correlation coefficient

At the initial stage of analysis, Equation 6 was implemented using β values derived through an iterative (trial-and-error) procedure, exploring a parameter range from 0.1 to 1.0. This method aimed to assess the model's sensitivity to variations in β, specifically regarding its effects on the correlation coefficient and the RSR, as shown in Figure 6.

The results obtained from Equation 5 using an iterative method showed that variations in β significantly affected the correlation coefficient. As presented in Figure 6, the relationship between the iterative β and the correlation coefficients showed a consistent pattern across all watersheds, with the optimal value ranging between 0.2 and 0.5, followed by a decreasing trend, except for Kuto. An exception was observed in Kuto, where the optimal beta value was significantly higher, reaching approximately 0.9, accompanied by a downward trend.

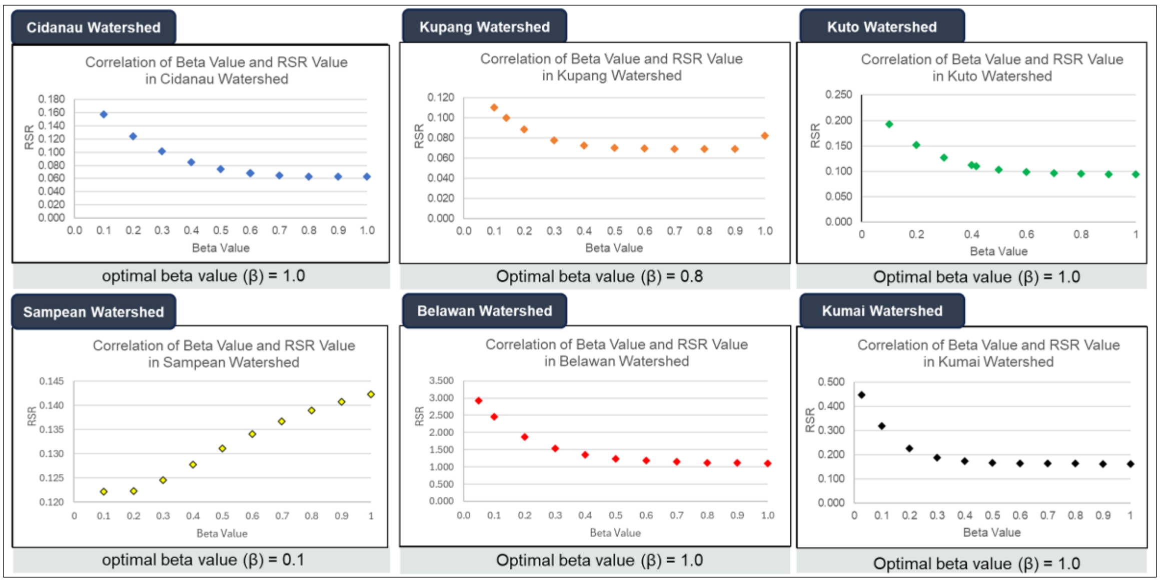


Figure 7. The influence of iterative beta value (β) on RSR value

The results obtained from Equation 6 showed that variations in β significantly affected the RSR value. As presented in Figure 7, the relationship between the iterative β and RSR value showed a consistent pattern across all watersheds, with the optimal β value ranging from 1.0, except for Kupang and Sampean. In Kupang, the optimal beta value was found at 0.8, followed by a rise in RSR values. Conversely, Sampean showed an early optimal β at 0.1, with an increasing trend in RSR. The refined results were compared with those obtained from Equations 2 (modified rational equation) and 6 (enhancement of the modified rational equation), using β values derived from Equation 6, as shown in Table 8.

Table 8. Comparative Analysis of Modified Rational Equation (a) without β; (b) β = A_{GWB}/A_{WS}; and β = based on trial and error

No.	Watersheds	Beta Value (β)	Correlation	RSR
1	Cidanau	a) Equation 2 (without β)	70.20%	0.066
		b) Equation 6 with A_{WS}/A_{GWB} (β= 0.603)	70.33%	0.068
		c) Equation 6 with Trial and Error (β= 0.401)	70.36%	0.085
2	Kupang	a) Equation 2 (without β)	63.07%	0.069
		b) Equation 6 with A_{WS}/A_{GWB} (β= 0.140)	63.17%	0.119
		c) Equation 6 with Trial and Error (β= 0.350)	63.15%	0.089
3	Kuto	a) Equation 2 (without β)	67.13%	0.094
		b) Equation 6 with A_{WS}/A_{GWB} (β= 0.417)	66.96%	0.110
		c) Equation 6 with Trial and Error (β= 0.952)	67.14%	0.094
4	Sampean	a) Equation 2 (without β)	58.08%	0.142
		b) Equation 6 with A_{WS}/A_{GWB} (β= 0.500)	58.39%	0.131
		c) Equation 6 with Trial and Error (β= 0.411)	58.39%	0.128
5	Belawan	a) Equation 2 (without β)	47.47%	1.106
		b) Equation 6 with A_{WS}/A_{GWB} (β= 0.048)	47.60%	2.921
		c) Equation 6 with Trial and Error (β= 0.899)	47.49%	1.112
6	Kumai	a) Equation 2 (without β)	41.24%	0.162
		b) Equation 6 with A_{WS}/A_{GWB} (β= 0.026)	41.26%	0.446
		c) Equation 6 with Trial and Error (β= 0.294)	41.35%	0.189

The iterative calibration process in Table 6 determined the optimal β coefficients for all selected watersheds, which enhanced the correlation coefficients between observed and simulated streamflow. Furthermore, the trial-and-error calibration showed lower Root Mean Square Error to Standard Deviation Ratio (RSR) values compared to previous model iterations for most watersheds. In Belawan, RSR values tended to increase, falling into the unsatisfactory range (RSR > 0.70). Kumai showed higher RSR values, but these remained within the 0.00 to 0.50 range, showing a 'very good' model performance. The optimal β values obtained varied among watersheds, showing that the correction factor significantly influenced baseflow calculations. This confirmed that the enhancement of the modified rational equation with the β parameter effectively enhanced model performance, as demonstrated by higher correlation coefficients and lower RSR values.

4. Conclusion

In conclusion, the modified rational equation shows reliable performance in simulating streamflow and estimating potential discharge within fully delineated watersheds of a single groundwater basin. Comparative analyses with other hydrological methods show that the modified rational equation achieves the highest correlation coefficients (except for Kuto) and Root Mean Square Error (RSR) values within the "very good" range (except for Belawan). This suggests that the modified equation offers a simplified but highly effective method, showing potential for assessing water availability in the selected watersheds. The inclusion of runoff, interflow, and baseflow parameters in the formulation of the modified rational equation contributes to a more comprehensive representation of streamflow processes. By increasing total discharge (Q), the model also provides a more accurate depiction of hydrological dynamics in fully delineated watersheds within a single groundwater basin. The introduction of β further enhances model performance by improving correlation coefficients and reducing RSR values, causing a significant improvement in the accuracy and reliability of discharge estimates. Among other methods, the modified rational equation performs best in small watersheds (<250 km²), with correlation values consistently above 60% in catchments like Cidanau, Kupang, and Kuto. However, the performance decreases with larger areas, showing suitability for small-scale hydrological systems where surface and subsurface flows correlate with the model's assumptions. For future study, the modified rational equation should be validated across a broader range, including both small and large catchments with diverse physical characteristics and hydrological conditions. This comprehensive validation would assess the equation's sensitivity, consistency, and predictive accuracy in various hydrological settings. Additionally, the application of the modified rational equation should cover fully delineated watersheds in more than one groundwater basin, which includes complex interactions between surface and subsurface water flows. This will require developing new analytical methods to account for complex water-flow dynamics. Moreover, refining the equation could establish a solid foundation for supporting effective water resource management in Indonesia.

5. Declarations

5.1. Author Contributions

Conceptualization, C.M., I.S., and M.F.; methodology, C.M., I.S., and M.F.; software, C.M. and M.F.F.; validation, C.M. and M.F.F.; formal analysis, C.M.; investigation, C.M.; resources, C.M.; data curation, C.M.; writing—original draft preparation, C.M. and M.F.F.; writing—review and editing, C.M. and M.F.F.; visualization, C.M.; supervision, I.S., M.F., and A.T.; project administration, C.M.; funding acquisition, C.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Savenije, H. H. G., & Van der Zaag, P. (2008). Integrated water resources management: Concepts and issues. Physics and Chemistry of the Earth, 33(5), 290–297. doi:10.1016/j.pce.2008.02.003.

[2] Shukla, B. K., Tripathi, A., Nagavi, J. C., Prasad, S., Sahoo, M., Chaudary, S., Ayush, & Verma, S. (2024). Integrated Water Resources Management (IWRM) in the Geospatial Epoch: An Ontological Dive into Sustainable Hydrological Governance. Sustainable Development and Geospatial Technology: Applications and Future Directions: Volume 2, 2, 1–22. doi:10.1007/978-3-031-65703-0_1.

[3] Khurshid, N., Kumar, R., Vishwakarma, D. K., Kumar, S., Pandit, B. A., Khan, I., Pukhta, M. S., & Yadav, K. K. (2025). Interaction Modeling of Surface Water and Groundwater: An Evaluation of Current and Future Issues. Water Conservation Science and Engineering, 10(1), 1–28. doi:10.1007/s41101-025-00360-5.

[4] Irvine, D. J., Singha, K., Kurylyk, B. L., Briggs, M. A., Sebastian, Y., Tait, D. R., & Helton, A. M. (2024). Groundwater-Surface water interactions research: Past trends and future directions. Journal of Hydrology, 644, 132061. doi:10.1016/j.jhydrol.2024.132061.

[5] Dobson, B., Liu, L., & Mijic, A. (2024). Modelling water quantity and quality for integrated water cycle management with the Water Systems Integrated Modelling framework (WSIMOD) software. Geoscientific Model Development, 17(10), 4495–4513. doi:10.5194/gmd-17-4495-2024.

[6] Lehmann, F., Vishwakarma, B. D., & Bamber, J. (2022). How well are we able to close the water budget at the global scale? Hydrology and Earth System Sciences, 26(1), 35–54. doi:10.5194/hess-26-35-2022.

[7] Meira Neto, A. A., Roy, T., de Oliveira, P. T. S., & Troch, P. A. (2020). An Aridity Index-Based Formulation of Streamflow Components. Water Resources Research, 56(9), 2020 027123. doi:10.1029/2020WR027123.

[8] Kheimi, M., & Abdelaziz, S. M. (2022). A Daily Water Balance Model Based on the Distribution Function Unifying Probability Distributed Model and the SCS Curve Number Method. Water (Switzerland), 14(2), 143. doi:10.3390/w14020143.

[9] Xue, J., & Gavin, K. (2008). Effect of rainfall intensity on infiltration into partly saturated slopes. Geotechnical and Geological Engineering, 26(2), 199–209. doi:10.1007/s10706-007-9157-0.

[10] Novák, V., & Hlaváčiková, H. (2019). Infiltration of water into soil. Theory and Applications of Transport in Porous Media, 32, 137–164. doi:10.1007/978-3-030-01806-1_10.

[11] McGuire, K. J., Klaus, J., & Jackson, C. R. (2024). Interflow, subsurface stormflow and throughflow: A synthesis of field work and modelling. Hydrological Processes, 38(9). doi:10.1002/hyp.15263.

[12] Briggs, M. A., Newman, C., Benton, J. R., Rey, D. M., Konrad, C. P., Ouellet, V., Torgersen, C. E., Gruhn, L., Fleming, B. J., Gazoorian, C., & Doctor, D. H. (2025). James Buttle Review: The Characteristics of Baseflow Resilience Across Diverse Ecohydrological Terrains. Hydrological Processes, 39(3), 70101. doi:10.1002/hyp.70101.

[13] Jakeman, A. J., Barreteau, O., Hunt, R. J., Rinaudo, J.-D., Ross, A., Arshad, M., & Hamilton, S. (2016). Integrated Groundwater Management. Springer, Cham, Switzerland. doi:10.1007/978-3-319-23576-9_1.

[14] Mursyid, B., Nur Fauzan, G., Haiqal Mahardika Sujud, M., & Agusti Sihab, R. (2025). Comparison of Rain-Flow Models FJ Mock and NRECA. Journal of Social Research, 4(8), 2219–2232. doi:10.55324/josr.v4i8.2725.

[15] Hidayat, M., & Nugroho, H. (2025). Comparison of Rainfall -Runoff Models with F.J. Mock and NRECA to Determine Water Availability of Rukoh Reservoir, Aceh. Teknik, 46(1), 73–86. doi:10.14710/teknik.v46i1.67951.

[16] Wang, B., Sun, H., Guo, S., Huang, J., Wang, Z., Bai, X., Gong, X., & Jin, X. (2023). Strategy for Deriving Sacramento Model Parameters Using Soil Properties to Improve Its Runoff Simulation Performances. Agronomy, 13(6). doi:10.3390/agronomy13061473.

[17] Zhou, J. Q., Li, C., Wang, L., Tang, H., & Zhang, M. (2021). Effect of slippery boundary on solute transport in rough-walled rock fractures under different flow regimes. Journal of Hydrology, 598, 126456. doi:10.1016/j.jhydrol.2021.126456.

[18] Crawford, N. H., & Thurin, S. M. (1981). Hydrologic estimates for small hydroelectric projects. Small Decentralized Hydropower Program, International Programs Division, National Rural Electric Cooperative Association, Arlington, United States.

[19] Mock, F. J. (1973). Land capability appraisal, Indonesia. Water availability appraisal-Basic study. Food and Agriculture Organization of the United Nations, Rome, Italy.

[20] Chouaib, W., Alila, Y., & Caldwell, P. V. (2021). Implications of a priori parameters on calibration in conditions of varying terrain characteristics: Case study of the SAC-SMA model in eastern united states. Hydrology, 8(2), 78. doi:10.3390/HYDROLOGY8020078.

[21] Froehlich, D. C. (2024). A Modified Rational Method Approach for Calculating First Flush Design Flow Rates to Mitigate Nonpoint Source Pollution from Stormwater Runoff. Hydrology, 11(2), 21. doi:10.3390/hydrology11020021.

[22] Kencanawati, M., Anwar, N., & Maulana, M. A. (2021). Modification of basic hydrology formulation based on an approach of the rational method at field measurement. IOP Conference Series: Earth and Environmental Science, 930(1), 12051. doi:10.1088/1755-1315/930/1/012051.

[23] Mayavani, C., Soekarno, I., Farid, M., & Taufiq, A. (2024). An improved equation for potential discharge estimation in groundwater basin delineated watershed. Results in Engineering, 24. doi:10.1016/j.rineng.2024.103238.

[24] Regulation No. 04/PRT/M/2015. (2015). Concerning the Criteria and Designation of River Regions. Ministry of Public Works and Housing. Regulation, Jakarta, Indonesia. Available online: https://peraturan.bpk.go.id/Details/159834/permen-pupr-no-04prtm2015-tahun-2015 (accessed on February 2026).

[25] Kodoatie, R. J., & Sjarief, R. (2010). Water spatial planning. Penerbit Andi, Yogyakarta, Indonesia. (In Indonesian).

[26] Regulation No. 2/2017. (2017). Concerning on Groundwater Basins in Indonesia. Ministry of Energy and Mineral Resources, Jakarta, Indonesia. Available online: https://peraturan.bpk.go.id/Details/142956/permen-esdm-no-2-tahun-2017 (accessed on February 2026).

[27] Kodoatie, R. J. (2021). Groundwater spatial planning. Penerbit Andi, Yogyakarta, Indonesia. (In Indonesian).

[28] Morbidelli, R., Saltalippi, C., Dari, J., & Flammini, A. (2021). A review on rainfall data resolution and its role in the hydrological practice. Water (Switzerland), 13(8). doi:10.3390/w13081012.

[29] Iliopoulou, T., & Koutsoyiannis, D. (2025). Have rainfall patterns changed? A global analysis of long-term rainfall records and Re-Analysis data. The Heritage Foundation, Washington, United States.

[30] SNI 2415:2016. (2016). Concerning Flood Discharge Measurement Methods. National Standardization Agency of Indonesia, Jakarta, Indonesia. (In Indonesian).

[31] Fayomi, G. U., Onyari, E. K., & Jaiyeola, A. T. (2024). Quantitative assessment of open drainage and storm water runoff capacity in Nigeria: Consequences and way forward. Case Studies in Chemical and Environmental Engineering, 9, 100766. doi:10.1016/j.cscee.2024.100766.

[32] Freeze, R. A., & Cherry, J. A. (1979). Groundwater prentice-hall. Englewood Cliffs, New Jersey, United States.

[33] Djukic, V., & Mihailovic, V. (2012). Analysis of groundwater regime on the basis of stream flow hydrograph. Facta Universitatis - Series: Architecture and Civil Engineering, 10(3), 301–314. doi:10.2298/fuace1203301d.

[34] Smerdon, B. D., Redding, T., & Beckers, J. (2009). An overview of the effects of forest management on groundwater hydrology. Journal of Ecosystems and Management. doi:10.22230/jem.2009v10n1a409.

[35] Sosrodarsono, S., & Takeda, K. (1980). Hydrology for irrigation. Pradnya Paramita, Jakarta, Indonesia. (In Indonesian).

[36] Sri, H. (1993). Hydrological Analysis. Gramedia Pustaka Utama, Jakarta, Indonesia. (In Indonesian).

[37] Soewarno, S. (1995). Hydrology: Application of Statistical Methods for Data Analysis (Volume 2). Nova, Bandung, Indonesia. (In Indonesian).

[38] D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, & T. L. Veith. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE, 50(3), 885–900. doi:10.13031/2013.23153.

[39] Soewarno, S. (1995). Hydrology: Application of Statistical Methods for Data Analysis (Volume 1). Nova, Bandung, Indonesia. (In Indonesian).

[40] Hair Jr, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2010). Multivariate data analysis. Pearson Education Limited, London, United Kingdom.