JURNAL geografi

https://jurnal.unimed.ac.id/2012/index.php/geo/article/view/73529
https://doi.org/ 10.24114/jg.v18i2.73529 - (Vol 18, No 2 – 2026)
available at http://jurnal.unimed.ac.id/2012/index.php/geo
e-issn (2549-7057) & p-issn (2085-8167)

Hydrological Regime and Q95 Discharge in the Upper Wampu Watershed, Karo Regency, Indonesia

Darnianti[1*] Abdul Rauf[2], Rosmadi Fauzi[3], Nisfariza Binti Mohd Noor[3], Rahmawaty[4], Miswar Budi Mulya[5]

[1]Department of Civil Engineering, Faculty of Science and Technology, Universitas Quality Medan, Indonesia
[2]Agrotechnology Study Program, Faculty of Agriculture, Universitas Sumatera Utara, Indonesia
[3]Department of Geography, Faculty of Arts and Social Sciences, Universiti Malaya, 50603 Kuala Lumpur, Malaysia
[4]Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Indonesia
[5]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Sumatera Utara, Indonesia

ARTICLE INFO

Article History:
Received: April 29, 2026
Revision: July 25, 2026
Accepted: July 29, 2026

Keywords:
Dependable Flow (Q95);
Baseflow–Quickflow Separation;
Hydrological Regime;
SWAT Model;
Tropical Watershed

Corresponding Author
Darnianti
E-mail:
darnianti@universitasquality.ac.id

ABSTRACT

Reliable streamflow is a critical indicator of water availability and hydrological resilience in tropical watersheds under increasing land-use pressure. This study quantified reliable low-flow conditions (Q95) and characterized hydrological regime dominance in the Upper Wampu Watershed, Karo Regency, Indonesia, using daily and monthly streamflow data from 2017–2024 analyzed through Flow Duration Curves (FDC), low-flow indices, and baseflow separation supported by SWAT model simulations. Mean annual discharge ranged from 45.1 to 66.4 m^3/s, increasing by about 8.7% between 2017–2020 and 2021–2024. Overall dependable flow (Q95) was estimated at 19.27 m^3/s, while monthly Q95 values ranged from 10.62 to 38.50 m^3/s, reflecting strong seasonal dependence on rainfall. Baseflow Q95 values were comparatively stable (21.47–41.59 m^3/s), yet the quickflow-to-baseflow ratio (Qq/Qb) exceeded 0.8 during wet months, indicating a runoff-dominated regime. Water balance analysis showed that surface runoff contributed more strongly to water yield than percolation, suggesting limited groundwater buffering capacity. SWAT model performance improved from calibration (PBIAS of -31.3% to -15.4%) to validation (+1.7%), supporting its reliability for hydrological regime assessment. These findings indicate that dependable water availability in the Upper Wampu Watershed is highly seasonal and rainfall-driven, with limited subsurface storage to buffer dry-season conditions. Strengthening infiltration through land conservation and sustainable watershed management is therefore essential to reduce hydrological vulnerability, particularly during dry seasons and intense rainfall events, in this and other environmentally stressed tropical mountainous watersheds.

INTRODUCTION

Reliable streamflow is a fundamental requirement for sustainable water resources management, particularly in tropical watersheds where river discharge is strongly influenced by seasonal rainfall and rapid hydrological response. As explained by Wang et al. (2023), water availability should not be assessed solely from total annual discharge, because the timing, persistence, and reliability of streamflow are equally important for domestic water supply, watershed resilience, and ecological sustainability. In this context, hydrological regime analysis and dependable flow assessment have become increasingly important, especially under conditions of hydroclimatic variability and growing pressure on catchment systems (Kuntoro et al., 2017; Liou & Kar, 2014; Sarigil et al., 2024).

The Upper Wampu Watershed is one of the strategic upland catchments in Karo Regency, North Sumatra, Indonesia, covering approximately 220,200 ha. The watershed functions as an important water catchment area that supports downstream water availability for domestic, agricultural, and ecological purposes. The area is characterised by mountainous topography and tropical climatic conditions with strong rainfall seasonality, making streamflow highly responsive to hydroclimatic variability. Recent land-cover changes indicate increasing anthropogenic pressure that may influence watershed hydrological processes. Between 2017 and 2024, plantation areas increased by 4.58%, settlement areas expanded by 24.67%, and forest cover increased by 2.25%, whereas grassland and open land decreased substantially (Darnianti et al., 2026). These changes have the potential to alter infiltration capacity, increase surface runoff, and affect the watershed's ability to maintain dependable flow during dry periods (Brontowiyono et al., 2022; François et al., 2024; Verburg et al., 2013).

The Upper Wampu Watershed also faces increasing challenges related to seasonal water availability and growing water demand. Population growth and regional development in Karo Regency have increased the demand for clean water, while seasonal rainfall variability affects the watershed's ability to maintain reliable streamflow during dry periods (François et al., 2024; Nag et al., 2024; Twisa et al., 2020). Lower dependable flow conditions during dry months indicate limited groundwater buffering capacity, which may reduce water availability when demand is relatively high. These conditions highlight the importance of evaluating seasonal water reliability to support sustainable water resource management in the region.

One of the most widely used indicators of dependable flow is Q95, which is defined as the discharge equalled or exceeded 95% of the time. This low-flow index is particularly useful for evaluating the reliability of raw water availability during dry periods, when river systems are under the greatest hydrological stress. In addition, hydrological regime analysis (Kuntoro et al., 2017; Nag et al., 2024; Sarigil et al., 2024) provides a broader understanding of how streamflow is generated and sustained through interactions among rainfall, surface runoff, infiltration, groundwater contribution, and catchment storage processes. Therefore, the combined use of Q95, flow duration curves, and baseflow–quickflow separation is effective for identifying whether a watershed is dominated by stable groundwater-supported flow or by rapid runoff response (Ojha et al., 2023; Shekar & Mathew, 2024).

Tropical upstream watersheds commonly exhibit strong hydroclimatic variability, particularly in relation to rainfall seasonality, which may significantly affect streamflow reliability across seasons (Qian et al., 2010). In the Upper Wampu Watershed, temperature and humidity remain relatively stable, whereas rainfall shows much stronger temporal variation. Rainfall variability is often the dominant climatic driver of streamflow fluctuation in tropical mountainous watersheds, particularly where catchment response to seasonal precipitation is rapid (Yang & Cao, 2021).

This climatic pattern is reflected in the streamflow behaviour of the Upper Wampu Watershed. Explain that strong seasonal contrasts in dependable flow indicate that annual discharge volume alone does not necessarily represent water reliability throughout the year Chen et al. (2024). In watersheds with rainfall-controlled hydrological systems, dependable flow may decline substantially during dry months even when annual average discharge appears relatively high (Abdelkebir et al., 2024; Liou & Kar, 2014). This condition suggests that streamflow in the Upper Wampu Watershed is highly seasonal and closely controlled by rainfall-driven processes. Further evidence from watershed hydrology indicates that runoff-dominated systems with low percolation generally have limited groundwater buffering capacity and weak long-term storage efficiency. Supangat et al. (2023) state that when surface runoff contributes much more strongly than groundwater recharge, river discharge becomes increasingly sensitive to direct rainfall input and less reliable during dry periods. Likewise, Daggupati et al. (2015) argue that such hydrological conditions increase vulnerability to both low-flow conditions and high-flow extremes, with important implications for water supply reliability and watershed management.

Several studies conducted in tropical watersheds have focused on land-cover change, climate variability, water quality assessment, and watershed water balance. These studies have contributed significantly to understanding watershed processes and water resource management. However, assessments of dependable flow (Q95) and hydrological regime characteristics remain relatively limited, particularly in tropical upland catchments where seasonal streamflow reliability is critical for water security (Hatmoko et al., 2020; Sarigil et al., 2024). In the Upper Wampu Watershed, previous studies have primarily examined land-cover dynamics and water quality conditions.

In contrast, the seasonal reliability of streamflow and the relative contributions of quickflow and baseflow have not been specifically evaluated (Sarigil et al., 2024). Furthermore, no previous study has integrated Flow Duration Curve (FDC) analysis, dependable flow (Q95), baseflow–quickflow separation, and annual water balance assessment to characterise the hydrological regime of the watershed.

Unlike previous hydrological studies that have primarily focused on annual discharge, water balance, or climate variability, this study integrates dependable flow (Q95) analysis, Flow Duration Curve (FDC), baseflow–quickflow separation, and SWAT-based water balance assessment to characterise the hydrological regime of the Upper Wampu Watershed (Herawati et al., 2015). By combining these approaches, this study provides a more comprehensive evaluation of seasonal streamflow reliability and watershed water availability, thereby contributing to sustainable water resource management in tropical upland catchments. Therefore, this study aims to quantify dependable flow (Q95) and characterise the hydrological regime of the Upper Wampu Watershed using streamflow analysis, flow duration curves, baseflow–quickflow separation, and water balance evaluation. By emphasising the seasonal reliability of discharge and the dominance of runoff versus baseflow processes, this study is expected to provide a stronger hydrological basis for water resource planning, watershed conservation, and sustainable raw water management in tropical upland catchments.

RESEARCH METHODS

Study Area

This study was conducted in the Upper Wampu Watershed, located in Karo Regency, North Sumatra, Indonesia, covering approximately 220,200 ha. Geographically, the watershed is located between 2°54′13.49″–4°01′06.28″ N and 97°54′28.26″–98°38′00.43″ E. The Upper Wampu Watershed represents an important tropical upstream catchment that contributes significantly to downstream raw water availability and exhibits strong hydrological sensitivity to rainfall variability.

The watershed is characterised by mountainous topography and tropical climatic conditions with marked rainfall seasonality, resulting in considerable temporal variations in streamflow characteristics. As an upland watershed, it plays an important role in supporting domestic, agricultural, and ecological water demands in downstream areas. Seasonal variations in rainfall and streamflow make the watershed suitable for evaluating dependable flow (Q95) and hydrological regime characteristics under tropical hydroclimatic conditions (Faddillah et al., 2023).

Climatic observations used in this study were obtained from the meteorological station operated by the Meteorological, Climatological, and Geophysical Agency (BMKG), which is representative of the watershed area. Streamflow observations were derived from hydrological monitoring records provided by the River Basin Organisation of Sumatra II (BWS Sumatera II) at the watershed outlet. The location of the study area is presented in Figure 1.

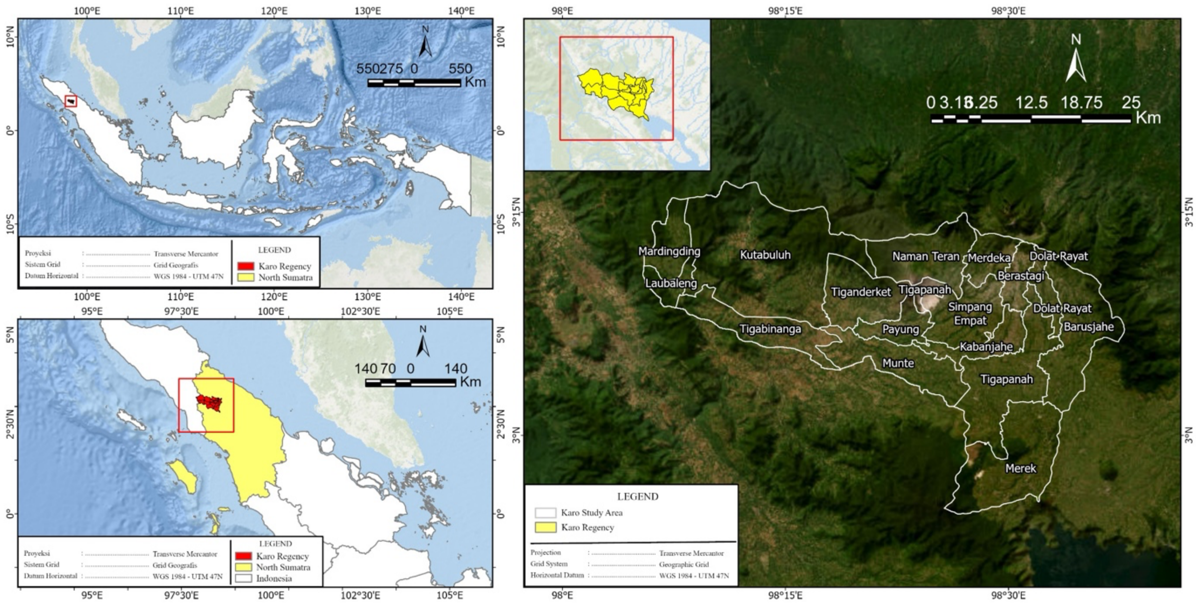


Figure 1. Location of the Upper Wampu Watershed in Karo Regency, North Sumatra, Indonesia (Source: Data Processing, 2026)

Data Sources

This research used both climatic and hydrological datasets with different temporal coverage according to their analytical objectives and data availability. Climatic data consisted of monthly and annual records of air temperature, relative humidity, rainfall, solar radiation, and wind speed for the period 2004–2024. The longer climatic record was used to characterise long-term hydroclimatic variability and seasonal climatic patterns influencing streamflow behaviour in the Upper Wampu Watershed. Hydrological analysis was based on daily and monthly streamflow data for the period 2017–2024, which were used to evaluate streamflow dynamics, dependable flow (Q95), and hydrological regime characteristics. This observation period represents the availability of continuous discharge records suitable for hydrological analysis and low-flow assessment.

Supporting simulation data were generated using the Soil and Water Assessment Tool (SWAT) model to analyse streamflow distribution and annual water balance components. Climate data were obtained from the Meteorological, Climatological, and Geophysical Agency (BMKG), whereas hydrological data were sourced from the River Basin Organisation of Sumatra II (BWS Sumatera II). Prior to analysis, all climatic and hydrological datasets were screened for completeness and continuity. The datasets used in this study consisted of complete observation records for their respective study periods (2004–2024 for climatic data and 2017–2024 for streamflow data), and no missing values were identified. Therefore, no missing-data infilling procedure was required. Only complete and continuous datasets were used for subsequent hydroclimatic and hydrological analyses. The climatic and hydrological datasets were obtained from official government institutions, namely BMKG and BWS Sumatera II, which routinely perform data quality control procedures before data dissemination.

Research Tools and Analytical Procedure

The main analytical tools used in this study were Microsoft Excel for tabulation and descriptive analysis, graphical analysis for hydroclimatic and streamflow patterns, and the SWAT model for hydrological simulation and water balance assessment. The methodological framework of this study consisted of five integrated analytical stages designed to characterise the hydrological regime and evaluate dependable water availability in the Upper Wampu Watershed. First, hydroclimatic variability analysis was conducted to identify long-term climatic patterns and their potential influence on streamflow behaviour. Second, streamflow analysis was performed to assess temporal variations in river discharge. Third, dependable flow (Q95) was estimated using the Flow Duration Curve (FDC) approach to evaluate seasonal flow reliability and low-flow conditions. Fourth, baseflow and quickflow components derived from SWAT model outputs were analysed to determine the dominant streamflow generation processes within the watershed. Finally, SWAT-based water balance analysis was conducted to assess watershed retention capacity, groundwater buffering characteristics, and the relative contributions of hydrological components to streamflow generation. The integration of these analytical stages provides a comprehensive assessment of seasonal streamflow reliability, watershed hydrological behaviour, and dependable water availability, thereby supporting sustainable water resources management in tropical upland watersheds.

Hydroclimatic Variability Analysis

Hydroclimatic variability analysis was conducted to support interpretation of streamflow behaviour in the watershed. The analysis focused on long-term variation in temperature, humidity, rainfall, solar radiation, and wind speed during 2004–2024. Descriptive statistical analysis was used to identify seasonal and interannual patterns, while the coefficient of variation was applied to compare the relative variability of climatic variables. This analysis was intended to identify the dominant climatic factor influencing streamflow fluctuation in the Upper Wampu Watershed.

Streamflow Analysis

Streamflow dynamics were assessed using outlet discharge data for 2017–2024. Daily, monthly, and annual discharge patterns were analysed to evaluate temporal variation and the watershed's general hydrological response. Mean streamflow values were compared between the periods 2017–2020 and 2021–2024 to identify shifts in discharge behaviour. This stage provided an initial overview of hydrological changes before conducting more specific analysis of dependable flow and hydrological regime dominance.

Flow Duration Curve and Q95 Analysis

Dependable flow was evaluated using the Flow Duration Curve (FDC) approach. Daily streamflow data were ranked from highest to lowest discharge, and exceedance probability was used to determine the percentage of time that a given discharge was equalled or exceeded (Sarigil et al., 2024). The exceedance probability was calculated using the Weibull plotting position method.

$$P = \frac{m}{n+1} \times 100 \quad \text{................(1)}$$

where P is the exceedance probability (%), m is the rank order of discharge values, and n is the total number of daily discharge observations.

The Q95 value, defined as the discharge equalled or exceeded 95% of the time, was used as an indicator of reliable low flow in the watershed, following (Sarigil et al., 2024). Monthly Q95 values were then derived to evaluate seasonal flow reliability and to identify months with potentially reduced raw water availability. Lower Q95 values were interpreted as indicating lower dependable flow and reduced dry-season water reliability, whereas higher Q95 values reflected better seasonal water availability (Hatmoko et al., 2020). Prior to analysis, the streamflow dataset was screened for completeness. No missing values were identified within the selected observation period; therefore, no missing-data treatment or infilling procedures were required.

Baseflow and Quickflow Separation

Monthly Q95 values of quickflow. To further characterise the hydrological regime, total streamflow was separated into baseflow and quickflow components using the hydrological outputs generated by the Soil and Water Assessment Tool (SWAT) model. Baseflow represents the relatively sustained contribution of groundwater discharge and subsurface storage to streamflow, whereas quickflow represents the rapid runoff response associated with rainfall events (Tang et al., 2021).

Moreover, baseflows were subsequently compared to evaluate their relative contributions to streamflow maintenance. The hydrological regime was interpreted using the Q95 quickflow-to-baseflow ratio (Qq/Qb), where a ratio below 0.5 indicated baseflow dominance, values between 0.5 and 0.8 represented transitional conditions, and values above 0.8 indicated quickflow dominance (Edwards et al., 2015). This classification was used to determine whether the Upper Wampu Watershed exhibited a relatively stable groundwater-supported regime or a runoff-dominated regime during different months of the year.

SWAT Model Simulation

Hydrological simulation was performed using the Soil and Water Assessment Tool (SWAT) to support the analysis of streamflow characteristics and watershed water balance. The SWAT model was used to simulate the spatial distribution of streamflow and to estimate annual water balance components, including rainfall, evapotranspiration, surface runoff, percolation, and water yield. These outputs were used to interpret dominant hydrological processes in the watershed and to support assessment of retention capacity and groundwater buffering (Corona et al., 2014). These hydrological outputs were subsequently used to derive the baseflow and quickflow components employed in the hydrological regime analysis. Because these streamflow components were generated internally by the SWAT model, no additional Baseflow Index (BFI) or recursive digital filtering procedures were applied in this study.

Calibration and Validation of the SWAT Model

The hydrological consistency of the SWAT model was evaluated through a manual calibration procedure. Because continuous daily discharge records were limited, parameter adjustment was conducted using annually aggregated hydrological statistics, particularly water yield and the major water-balance components. The calibration followed a process-based approach in which sensitive parameters were adjusted iteratively within physically reasonable ranges until the simulated annual water yield and the distribution of surface runoff, baseflow, evapotranspiration, and groundwater recharge were consistent with the available hydrological information and watershed characteristics (Copeland et al., 2025; Gay et al., 2025; Grey et al., 2014).

A two-year warm-up period from 2015 to 2016 was applied to stabilise the initial conditions of soil moisture and groundwater storage. Calibration used observed data from 2017, 2021, and 2022, while validation used data from 2023. The main parameters adjusted during calibration were CN2, representing rainfall partitioning into infiltration and surface runoff under watershed land-cover conditions, and ESCO, which controls soil evaporation and soil water extraction dynamics. Model performance was evaluated using Per cent Bias (PBIAS), and the resulting model performance ranged from good to very good, supporting its use for hydrological regime and water balance assessment (Heryani et al., 2022).

Water Balance and Hydrological Regime Assessment

Annual water balance analysis was used to determine how incoming rainfall was partitioned into evapotranspiration, surface runoff, percolation, and water yield. The relative contribution of these components was used to interpret watershed retention capacity and hydrological responsiveness. A watershed was considered runoff-dominated when water yield was largely generated by surface runoff, quickflow dominance occurred during wet months, and percolation remained relatively small compared with rainfall input. In contrast, stronger baseflow dominance and higher percolation indicated better subsurface storage and more stable low-flow support.

Overall, the integration of hydroclimatic variability analysis, FDC-based Q95 estimation, baseflow–quickflow separation, SWAT simulation, and annual water balance evaluation was used to characterise the hydrological regime of the Upper Wampu Watershed and assess its implications for dependable water availability (Sarigil et al., 2024). Monthly Q95 values were derived by constructing Flow Duration Curves separately for each calendar month using daily streamflow records aggregated over the period 2017-2024.

RESULTS AND DISCUSSION

Hydroclimatic characteristics of the Upper Wampu Watershed.

The hydroclimatic characteristics of the Upper Wampu Watershed indicate that rainfall was the most variable climatic component during the observation period. At the interannual scale, the average daily rainfall ranged from 4.84 mm/day in 2015 to 8.04 mm/day in 2011, indicating clear contrasts between relatively dry and wet years during the study period. The monthly rainfall pattern is also illustrated in Figure 2.

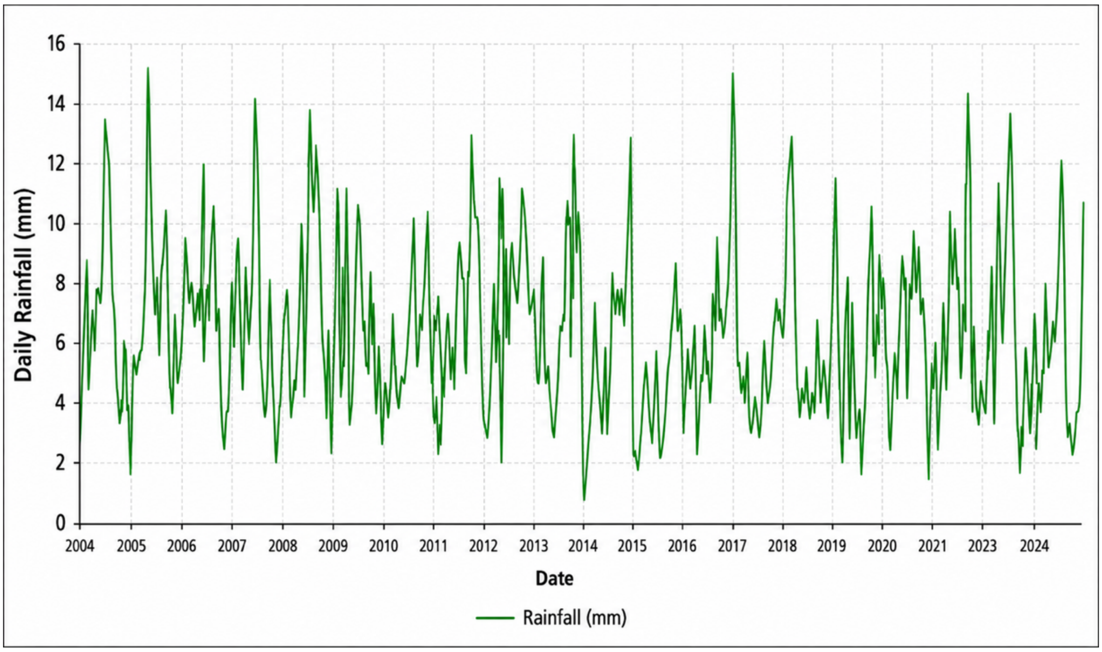


Figure 2. Monthly Precipitation Pattern 2004–2024 (Source: Data Processing, 2026)

Figure 2 displays the daily rainfall record for the Upper Wampu Watershed from 2004 to 2024. Daily values fluctuate within a fairly consistent range of roughly 0 to 15 mm/day throughout the observation period, with no discernible long-term upward or downward trend. Within this range, rainfall shows a recurring annual cycle; periods of relatively higher and more frequent rainfall alternate with periods of lower, more sporadic rainfall on a roughly yearly basis, superimposed on considerable day-to-day scatter.

This combination of short-term variability and a repeating annual cycle indicates that rainfall in the Upper Wampu Watershed operates at two overlapping time scales. Day-to-day fluctuations reflect the episodic nature of individual rainfall events, while the recurring yearly pattern reflects the broader seasonal cycle that governs when wetter and drier conditions are more likely to occur. Because streamflow generation responds to both scales, brief high-intensity rainfall days can drive short-lived runoff peaks even during months that are climatologically drier on average, while the underlying seasonal cycle still shapes the broader pattern of water availability across the year.

To separate the seasonal component from this day-to-day variability, Table 1 presents the average monthly rainfall values computed from the same 2004–2024 record. Aggregating the daily data by calendar month makes the underlying seasonal cycle more explicit and provides the numerical basis for the subsequent flow duration curve and dependable flow (Q95) analysis.

Table 1. Average Monthly Rainfall (Seasonal Rainfall Pattern)

Month	Average Rainfall (mm/day)
January	5.36
February	4.41
March	5.72
April	5.53
May	6.67
June	5.22
July	5.92
August	7.06
September	9.23
October	10.46
November	9.62
December	8.99

(Source: BMKG, 2004–2024)

Table 1 shows that average rainfall varies considerably across the calendar year, ranging from 4.41 mm/day in February to 10.46 mm/day in October, a difference of more than twofold between the driest and wettest months. The months from January through July remain relatively close to one another, generally between 4.41 and 7.06 mm/day, whereas September through December form a distinctly wetter cluster, each exceeding 8.9 mm/day. This grouping confirms that the Upper Wampu Watershed experiences a single extended wet season concentrated in the latter part of the year rather than several shorter wet periods spread evenly across the months.

This intra-annual pattern, however, only describes how rainfall is distributed within an average year and does not capture how much that pattern itself shifts from one year to the next. Because the daily record spans twenty-one years, some years may have been considerably wetter or drier overall than the long-term monthly averages suggest. Examining year-to-year variation in annual rainfall is therefore necessary to complete the hydroclimatic picture of the watershed, as presented in Table 2.

Table 2. Annual Average Daily Rainfall (2004–2024)

Years	Annual Daily Average (mm/day)
2004	7.01
2005	7.36
2006	8.03
2007	7.76
2008	7.83

2009	7.59
2010	7.04
2011	8.04
2012	7.62
2013	7.63
2014	6.06
2015	4.84
2016	6.91
2017	7.16
2018	6.39
2019	5.85
2020	6.94
2021	7.81
2022	7.67
2023	6.51
2024	6.58

(Source: BMKG, 2004–2024)

Table 2 shows those interannual differences directly, with annual average daily rainfall ranging from 4.84 mm/day in 2015 to 8.04 mm/day in 2011, a difference of roughly 66 per cent between the driest and wettest years on record. Across the full 2004–2024 period, the annual averages cluster mostly between 6.5 and 8.0 mm/day, with 2015 standing out as a notable low outlier and 2011 as the corresponding high point. No clear long-term upward or downward trend is apparent in the sequence, suggesting that the variability is dominated by year-to-year fluctuation rather than a sustained climatic shift over the observation period.

Tables 1 and 2 describe two distinct but complementary sources of hydroclimatic variability in the Upper Wampu Watershed: a recurring seasonal cycle that concentrates rainfall in the September–December period each year, and an interannual variability that determines whether a given year is comparatively wet or dry overall. Both dimensions are essential for the subsequent hydrological regime analysis, since a watershed's dependable flow depends not only on the reliability of its wet season within a typical year but also on how consistently that seasonal pattern is delivered across successive years.

The findings indicate that the Upper Wampu Watershed exhibits a rainfall-responsive hydrological regime, in which streamflow dynamics are strongly controlled by seasonal rainfall variability. Among the hydroclimatic variables analysed, rainfall showed the greatest temporal fluctuation, whereas temperature and relative humidity remained comparatively stable. This pattern suggests that rainfall is the primary driver of discharge variation in the watershed. The observed increase in monthly rainfall from August and its peak in October was followed by substantial variation in streamflow during 2017–2024, with mean annual discharge ranging from 45.1 m^3/s to 66.4 m^3/s. In addition, the increase in mean outlet discharge from 54.725 m^3/s in 2017–2020 to 59.475 m^3/s in 2021–2024 indicates that hydrological response in the watershed has become more dynamic over time. This finding is consistent with studies in tropical catchments showing that rainfall seasonality exerts a dominant influence on river discharge, especially in mountainous upstream watersheds with rapid runoff response.

Streamflow Characteristics

The spatial distribution of streamflow derived from the SWAT model shows that low-flow classes were concentrated in upstream and peripheral headwater areas. At the same time, the highest discharge was located along the northwestern main channel near the outlet (Figure 3). Spatial Distribution of Streamflow in the Upper Wampu Watershed (2017–2024). Figure 3 shows daily, monthly, and annual fluctuations in discharge during 2017–2024. Mean annual outlet discharge ranged from 45.1 m³/s to 66.4 m³/s, indicating considerable interannual variability. A comparison between the two four-year observation periods (2017–2020 and 2021–2024) showed that the mean discharge increased from 54.725 m³/s to 59.475 m³/s, representing an increase of approximately 8.68%. This comparison was conducted to describe temporal variations in streamflow over the study period and does not imply a long-term trend analysis.

While the discussion above characterises how streamflow in the Upper Wampu Watershed varies over time, it does not indicate where within the watershed that streamflow is generated or how discharge magnitude differs across the drainage network. Because the SWAT model simulates hydrological processes at the sub-basin level rather than only at the watershed outlet, its output can also be used to examine the spatial distribution of streamflow across the catchment, providing a complementary perspective to the temporal analysis presented previously.

This spatial dimension is particularly relevant given the mountainous topography and extensive tributary network of the Upper Wampu Watershed, where discharge magnitude is expected to vary considerably between small headwater channels and the larger main stem near the outlet. Identifying this spatial pattern helps clarify which parts of the watershed contribute most strongly to overall water availability and which remain comparatively minor in terms of discharge volume, information that is not captured by outlet-based time series alone.

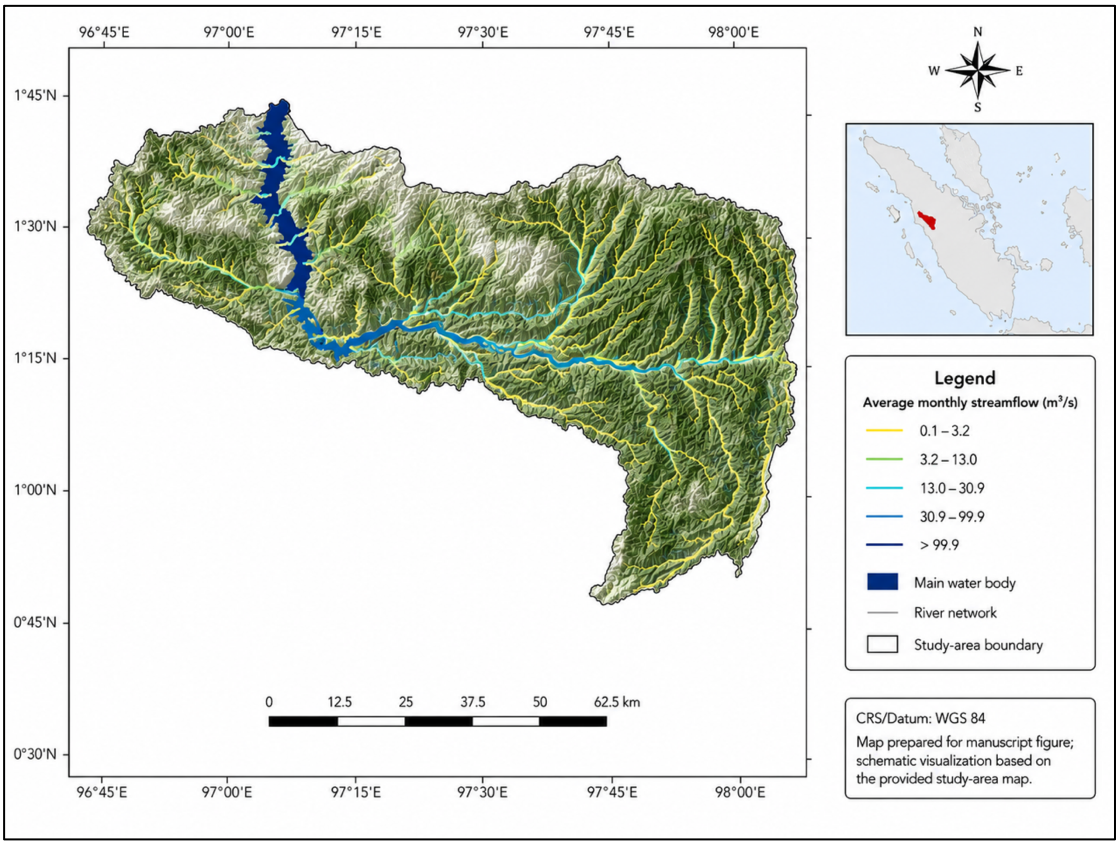
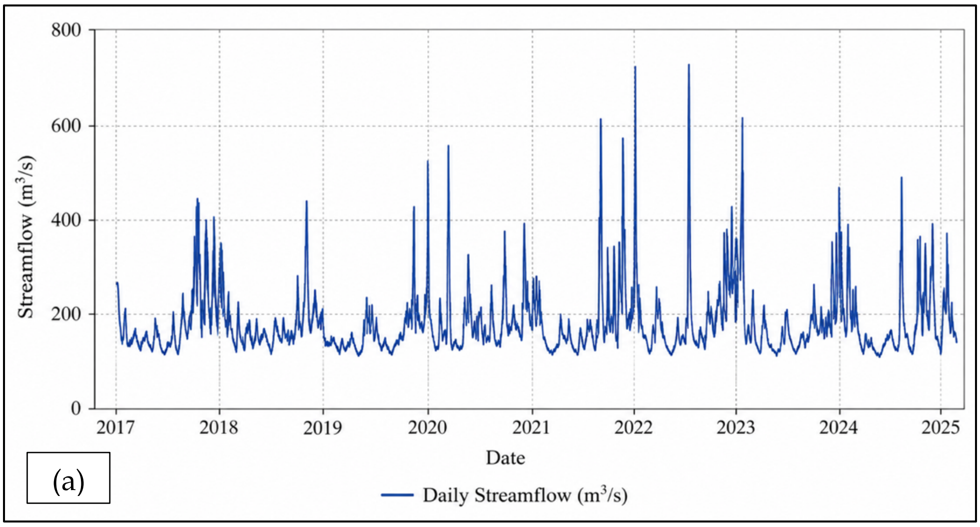


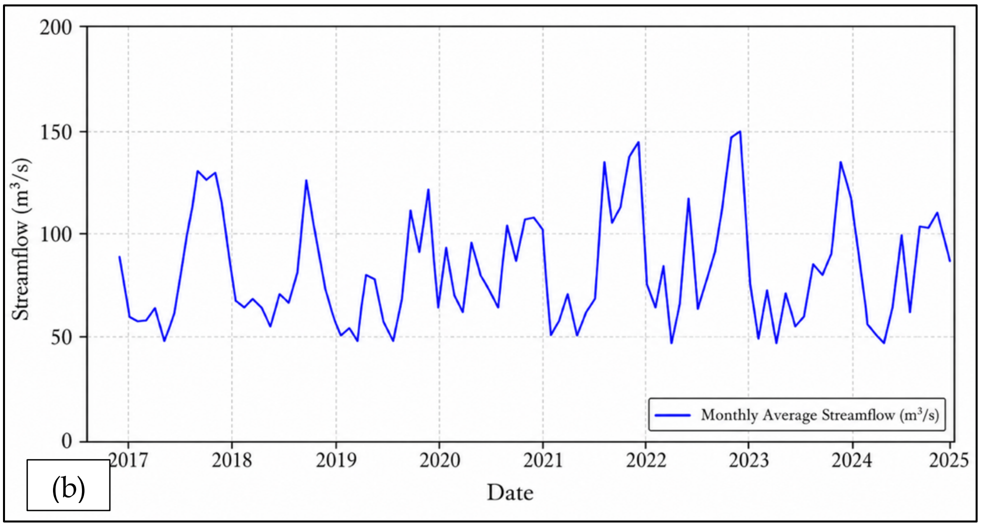
Figure 3. Spatial Distribution of Streamflow in the Upper Wampu Watershed (2017–2024) (Source: Data Processing, 2026)

The spatial pattern shown in Figure 3 follows the expected structure of a dendritic drainage network. The smallest tributaries in the upstream and peripheral headwater areas, distributed across the eastern and southern portions of the watershed, fall within the lowest streamflow classes. As these tributaries converge toward the northwestern part of the catchment, discharge increases progressively through the intermediate classes, reaching the highest streamflow range along the main channel near the watershed outlet. This progression reflects the cumulative contribution of drainage area, where discharge at any point in the network is a function of the upstream catchment area it collects rather than of local rainfall alone.

This spatial structure has practical implications for water resource planning in the watershed. Because the highest and most concentrated discharge occurs along a relatively narrow stretch of the main channel near the outlet, this reach represents the primary point of dependable water availability for downstream domestic, agricultural, and ecological users, while the headwater tributaries, despite their lower absolute discharge, remain critical for sustaining baseflow contributions throughout the network.

The spatial pattern in Figure 3 complements the temporal variability discussed previously, together the two perspectives show not only how much streamflow fluctuates over time but also where within the watershed that streamflow is generated and concentrated. To complement the spatial pattern shown in Figure 3, Figure 4 presents streamflow variability at three temporal resolutions for the 2017–2024 observation period: daily, monthly, and annual average discharge at the watershed outlet. Examining these three scales together allows short-term flood response, seasonal cyclicity, and longer-term interannual variation to be distinguished within the same discharge record.





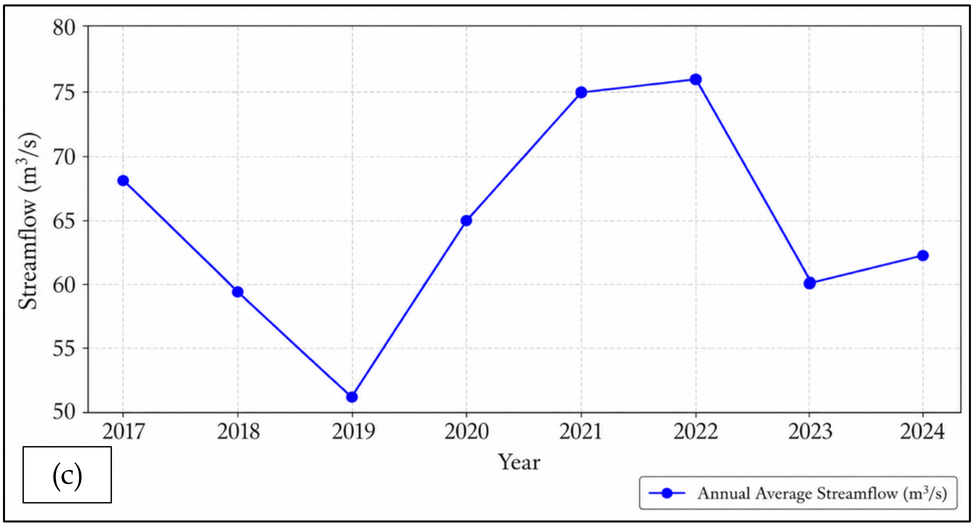


Figure 4. Streamflow variability in the Upper Wampu Watershed: (a) daily streamflow from 2017 to 2025; (b) monthly mean streamflow from 2017 to 2025; and (c) annual mean streamflow from 2017 to 2024 (Source: Data Processing, 2026)

The daily streamflow record (Figure 4a) shows a recurring pattern of a relatively stable base condition, generally fluctuating between 100 and 150 m^3/s, punctuated by sharp, short-lived discharge peaks that occasionally exceed 700 m^3/s, most notably around 2022 and 2023. These peaks are narrow and quickly recede, indicating a rapid catchment response in which discharge rises sharply during intense rainfall events and declines shortly afterwards rather than remaining elevated for extended periods. This flashy behaviour is characteristic of mountainous tropical watersheds with limited storage capacity, where surface runoff dominates the immediate response to rainfall.

When aggregated to monthly averages (Figure 4b), this short-term flashiness is smoothed out, revealing a clearer recurring seasonal cycle. Monthly discharge oscillates between roughly 35–50 m^3/s during drier periods and 100–150 m^3/s during wetter periods, with the highest monthly averages occurring around 2022–2023. This seasonal rise and fall aligns with the wet-season concentration identified earlier in the rainfall analysis, reinforcing that streamflow in the Upper Wampu Watershed is primarily rainfall-driven rather than governed by sustained baseflow contributions. The annual averages (Figure 4c) further show that this seasonal cycle operates within a broader pattern of interannual variability: discharge declined from about 68 m^3/s in 2017 to a low of approximately 51 m^3/s in 2019, then rose steadily to a peak of around 75–76 m^3/s in 2021–2022, before declining again to roughly 60–62 m^3/s in 2023–2024. Rather than following a simple long-term trend, annual discharge appears to fluctuate in multi-year cycles, consistent with the interannual rainfall variability described earlier and underscoring the importance of evaluating dependable flow (Q95) over a sufficiently long observation period rather than relying on any single year as representative of typical conditions.

Dependable flow (Q95)

The dependable flow (Q95) derived from the total streamflow data for the period 2017–2024 was estimated at 19.27 m^3/s. This value represents the discharge that is equalled or exceeded during approximately 95% of the observation period and serves as an indicator of reliable water availability in the Upper Wampu Watershed. The monthly dependable flow analysis reveals a strong seasonal pattern in the Upper Wampu Watershed. As presented in Table 3, monthly Q95 values ranged from 10.62 m³/s in April to 38.50 m³/s in November. Lower Q95 values were observed from February to August, whereas markedly higher values occurred from September to December. This pattern indicates that streamflow reliability varied substantially across seasons, with the dry-season and transition months showing lower dependable flow than the wet-season months.

Table 3. Monthly Dependable Flow (Q95) Values in the Upper Wampu Watershed (2017–2024)

Month	Q95 (m³/s)
January	25.58
February	13.92
March	15.13
April	10.62
May	13.50
June	14.29
July	17.54
August	13.69
September	36.88
October	35.34
November	38.50
December	38.01

(Source: Author's analysis based on streamflow data from BWS Sumatera II, 2017–2024)

The seasonal contrast in Table 3 mirrors the rainfall pattern identified earlier in Table 1, where September through December were established as the wettest months of the year. This correspondence indicates that dependable low-flow conditions in the Upper Wampu Watershed are directly governed by the seasonal rainfall cycle rather than by sustained groundwater storage, since Q95 values rise and fall in step with monthly rainfall rather than remaining relatively constant across seasons. The nearly fourfold difference between the lowest Q95 in April (10.62 m³/s) and the highest in November (38.50 m³/s) further suggests that raw water planning based solely on the overall annual Q95 of 19.27 m³/s would understate the degree of water scarcity risk during the February–August period.

This seasonal dependence on rainfall also points toward the underlying hydrological mechanism responsible for the pattern, namely the relative balance between quickflow and baseflow contributions to total streamflow. If dependable flow were primarily sustained by groundwater discharge, monthly Q95 values would be expected to remain comparatively stable throughout the year even as rainfall varies. The pronounced seasonal swing observed here instead suggests that quickflow, generated directly from rainfall-driven surface runoff, plays a substantial role in shaping monthly water availability. This hypothesis is examined more directly in the following section through baseflow–quickflow separation derived from the SWAT model outputs.

Baseflow and quick flow characteristics

The baseflow component also exhibited seasonal variation, but with a relatively narrower range than total dependable flow. As shown in Table 4, monthly Q95 baseflow values ranged from 21.47 m³/s to 41.59 m³/s. The lowest values occurred in January and May, while the highest values were recorded in October, November, and December. The monthly ratio between quick flow and baseflow is presented in Table 3, where Qq/Qb values ranged from 0.43 to 1.19. Ratios above 0.8 occurred in January, September, and October, while lower values occurred in February and April. These data indicate clear monthly contrasts in the relative contribution of quick flow and baseflow to river discharge.

Building on the total dependable flow (Q95) results discussed above, the baseflow component derived from the SWAT model separation was examined to determine how much of that dependable flow is sustained by subsurface storage rather than direct surface runoff. Table 4 presents the monthly Q95 values for baseflow (Qb) across the same 2017–2024 observation period.

Table 4. Monthly Q95 Values of Baseflow (Qb) in the Upper Wampu Watershed (2017–2024)

Month	Q95 Qb (m^3/s)
January	21.47
February	31.43
March	23.76
April	24.89
May	21.47
June	27.16
July	28.85
August	24.93
September	31.54
October	34.53
November	39.95
December	41.59

(Source: Author's analysis based on SWAT model baseflow separation using streamflow data from BWS Sumatera II, 2017–2024)

Monthly baseflow Q95 values range from 21.47 m^3/s in January and May to 41.59 m^3/s in December, a span that is proportionally narrower than the nearly fourfold variation observed in total dependable flow in Table 3. This comparatively tighter range indicates that baseflow, sustained by subsurface storage and gradual groundwater release, fluctuates less across seasons than total streamflow does. In practical terms, this means that even during drier months, subsurface contributions continue to provide a partial buffer against complete flow depletion, preventing dependable flow from collapsing entirely when rainfall is low.

At the same time, baseflow alone cannot fully account for the seasonal pattern already observed in total Q95. Because total dependable flow rises and falls more sharply than baseflow across the year, the difference between the two must be attributed to the quickflow component, the rapid runoff response generated directly by rainfall events. This gap is most pronounced during the wetter months of September through December, when total Q95 approaches its seasonal peak while baseflow increases only moderately by comparison. The relative contribution of quickflow versus baseflow to this pattern, expressed through the Qq/Qb ratio, is examined in more detail in the following analysis.

SWAT Model Performance and Annual Water Balance

The SWAT model performance is summarised in Table 5. The calibration and validation results showed PBIAS values ranging from -31.3% to +1.7%, indicating variable but generally acceptable model performance for hydrological interpretation. Annual water balance components are presented in Table 8, which shows rainfall values between 2376.67 mm and 2853.47 mm, percolation between 254.40 mm and 260.79 mm, and water yield between 1451.56 mm and 1923.31 mm. Annual water balance analysis showed rainfall values ranging from 2,376.67 to 2,853.47 mm, percolation values ranging from 254.40 to 260.79 mm, and water yield values ranging from 1,451.56 to 1,923.31 mm. The relatively low percolation values compared with total rainfall and water yield indicate limited groundwater recharge and buffering capacity in the Upper Wampu Watershed.

The Q95 analysis further confirms that dependable flow in the Upper Wampu Watershed is highly seasonal. Similar seasonal patterns of dependable flow have also been reported in tropical mountainous watersheds, where streamflow reliability is strongly influenced by rainfall seasonality and catchment storage characteristics. Monthly Q95 values ranged from 10.62 m^3/s in April to 38.50 m^3/s in November, indicating a marked contrast between dry-season and wet-season flow reliability. In practical terms, this means that high discharge during wet months does not necessarily ensure sufficient water availability during drier periods. (Shao et al., 2020) Similarly, dependable flow is a sensitive indicator of seasonal water security because it reflects not only total discharge volume but also the persistence of low flow over time. In the present study, baseflow-derived Q95 values were relatively more stable than total Q95, suggesting that subsurface storage still contributes to flow maintenance. However, the Qq/Qb ratio exceeded 0.8 in January, September, and October, indicating that quickflow dominated during wetter months. According toSarigil et al. (2024), such conditions are typical of rainfall-driven watersheds in which storm runoff contributes more strongly than delayed groundwater release. This interpretation is also supported by Hövel et al. (2024), who noted that runoff-dominated systems tend to show stronger flow variability and weaker dry-season buffering capacity.

Before evaluating the accuracy of the SWAT simulation, it is necessary to first establish the observed hydrological baseline against which the model output was compared. Table 5 presents the annual average flow depth of the Wampu Watershed for the years used in the calibration and validation process, expressed in millimetres to allow direct comparison with the model's simulated output.

Table 5. Annual Average Flow Depth of the Wampu Watershed

Year	Flow Depth (mm)
2017	2443,8
2021	2274
2022	2319
2023	1427,52

(Source: Indonesian Environmental Statistics, BPS, 2019, 2023, 2024, 2025)

The observed flow depth in Table 5 shows considerable year-to-year variation, ranging from a high of 2,443.8 mm in 2017 to a low of 1,427.52 mm in 2023, a decline of more than 40 per cent between these two years. The intermediate years, 2021 and 2022, recorded relatively similar values of 2,274 mm and 2,319 mm, suggesting a period of comparative stability before the sharp drop observed in 2023. This pattern indicates that, despite the seasonal rainfall regularity established earlier, the watershed's annual water yield is still subject to substantial interannual fluctuation, reinforcing the earlier observation that no single year can be treated as fully representative of long-term hydrological conditions in the Upper Wampu Watershed.

These four years, spanning both comparatively wet and comparatively dry conditions, were used as the observed reference dataset for the SWAT model. The model was calibrated using the 2017, 2021, and 2022 records and subsequently validated using the 2023 record. Table 6 summarises the resulting comparison between observed and simulated flow depth for each year, together with the corresponding Per-cent Bias (PBIAS) values and their qualitative performance evaluation.

Table 6. Statistical Test Results of Flow Depth Calibration and Validation (mm)

Stage	Year	Observed (mm)	Simulated (mm)	PBIAS (%)	Evaluation
Calibration	2017	2443,8	1678,3	-31,3	Unsatisfactory
	2021	2274,0	1923,3	-15,4	Good
	2022	2319,0	1914,0	-17,5	Good
Validation	2023	1427,5	1451,6	+1,7	Very Good

(Source: Author's analysis based on SWAT model calibration and validation results, 2017, 2021–2023)

As shown in Table 6, model performance varied noticeably across the calibration years, ranging from an unsatisfactory result in 2017 (PBIAS of -31.3%) to good agreement in 2021 and 2022 (-15.4% and -17.5%, respectively). The comparatively poor performance in 2017 is likely attributable to its position immediately following the model's warm-up period, during which simulated soil moisture and groundwater storage had not yet fully stabilised to match observed conditions. Performance improved considerably during validation, with the 2023 result showing a PBIAS of only +1.7%, classified as very good. This improvement from calibration to validation indicates that, once the model's initial conditions had stabilised, it was able to reproduce the watershed's hydrological behaviour with a good degree of reliability, supporting its subsequent use for annual water balance analysis.

The annual water balance provides additional evidence of runoff dominance in the Upper Wampu Watershed. Rainfall ranged from 2376.67 mm to 2853.47 mm, while percolation remained relatively low at 254.40–260.79 mm. At the same time, water yield ranged from 1451.56 mm to 1923.31 mm. Water balance analysis indicated that surface runoff was an important contributor to water yield, whereas percolation contributed a comparatively smaller fraction, indicating a runoff-dominated hydrological regime and limited groundwater buffering capacity.

This distribution indicates that most incoming rainfall is rapidly converted into direct runoff rather than stored in the soil or transferred into groundwater recharge. Liu et al. (2024) emphasised that watersheds with low percolation and high runoff contribution generally have limited retention capacity, making streamflow more sensitive to rainfall pulses and less reliable during dry periods. A similar hydrological condition was reported by Hövel et al. (2024) and Nag et al. (2024), who observed a pronounced difference between wet-season high flows and dry-season low flows in watersheds with limited natural and aquifer storage. Under such conditions, abundant streamflow during the wet season does not necessarily ensure sustained water availability during the dry season because groundwater contributions may be insufficient to maintain low flows. Therefore, although the Upper Wampu Watershed produces a relatively high annual water yield, its capacity to sustain dependable low flow remains limited (Darnianti et al., 2026).

These results have important implications for watershed management and water security in Karo Regency. The findings suggest that sustainable water availability depends not only on annual discharge magnitude but also on the watershed's capacity to regulate, retain, and gradually release water across seasons. Limited groundwater buffering and rapid runoff processes reduce dry-season flow persistence, making enhanced infiltration and subsurface water storage essential for sustaining dependable water availability (Lu et al., 2022; Montanari, 2006). In a watershed where hydrological processes are dominated by rapid runoff, efforts to improve infiltration and strengthen subsurface storage become essential.

Argued that land conservation, vegetation improvement, and soil-water retention measures are critical for enhancing baseflow support and reducing hydrological extremes (Banjara et al., 2024; Copeland et al., 2025; Leta et al., 2021). In the context of the Upper Wampu Watershed, such measures may include maintaining vegetation cover, reducing land degradation on hillslopes, improving infiltration zones, and limiting excessive surface runoff. Thus, the present study highlights that dependable flow analysis, combined with hydrological regime assessment, provides an important basis for designing watershed management strategies aimed at improving dry-season water reliability and long-term raw water sustainability (Narendra et al., 2021).

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

D.D. Conceptualisation, methodology, investigation, data curation, formal analysis, writing – original draft, visualisation, AND project administration. **A.R.** Methodology, formal analysis, validation, investigation, and writing – review & editing. **R.F.** Data curation, hydrological analysis, visualisation, software, and writing – review & editing. **N.B.M.N.** Investigation, resources, validation, and writing – review & editing. **R.R.** Supervision, methodology, validation, interpretation of results, and writing – review & editing. **M.B.M.** Supervision, resources, validation, and writing – review & editing. All authors have read and approved the final version of the manuscript.

CONCLUSION

This study concludes that the Upper Wampu Watershed exhibits a rainfall-responsive hydrological regime with strong seasonal variation in dependable flow. The analysis shows that rainfall is the main driver of streamflow fluctuation, while Q95 values indicate that flow reliability declines substantially during dry periods and increases during wetter months. The relatively stable baseflow component suggests some contribution from subsurface storage, whereas the dominance of quickflow during wet months and the important contribution of surface runoff to streamflow generation indicate that the watershed is predominantly runoff-dominated with limited groundwater buffering capacity. As a result, high water yield during the wet season does not necessarily guarantee reliable water availability during the dry season. These findings demonstrate that evaluating dependable flow and hydrological regime provides an important basis for understanding seasonal water security in the Upper Wampu Watershed. These findings highlight the importance of improving infiltration, enhancing watershed retention capacity, and strengthening land conservation measures to support more stable low-flow conditions and sustainable water resource management in tropical upland watersheds.

FUNDING

This research does not receive external funding.

ACKNOWLEDGMENT

The authors would like to thank BMKG and BWS Sumatera II for providing the climatic and hydrological data used in this study. This research forms part of the doctoral dissertation conducted at the Natural Resources and Environmental Management Doctoral Program, Universitas Sumatera Utara. The authors also gratefully acknowledge all parties who supported the completion of this research.

The author would like to thank Yayasan Konservasi Pesisir Indonesia for organising the 2026 International Conference on Coastal Ecosystems and Sustainable Development (CoESDev 2026), which provided an international forum for the author to present the results of this research. The author also thanks all parties who provided support and assistance during the research.

REFERENCE LIST

Abdelkebir, B., Mokhtari, E., & Engel, B. (2024). Assessment of land use and land cover changes on hydrological responses in the Wadi Soummam watershed, Algeria using the HEC–HMS model. Water Practice and Technology, 19(9), 3555–3577.

https://doi.org/10.2166/wpt.2024.224

Banjara, M., Bhusal, A., Ghimire, A. B., & Kalra, A. (2024). Impact of Land Use and Land Cover Change on Hydrological Processes in Urban Watersheds: Analysis and Forecasting for Flood Risk Management. Geosciences (Switzerland), 14(2). https://doi.org/10.3390/geosciences14020040

Brontowiyono, W., Asmara, A. A., Jana, R., Yulianto, A., & Rahmawati, S. (2022). Land-Use Impact on Water Quality of the Opak Sub-Watershed, Yogyakarta, Indonesia. Sustainability (Switzerland), 14(7), 1–21. https://doi.org/10.3390/su14074346

Chen, D., Liu, J., & Tang, Q. (2024). Water Resources in the Lancang-Mekong River Basin: Impact of Climate Change and Human Interventions. Springer Nature Singapore Pte Ltd. https://doi.org/10.1007/978-981-97-0759-1

Copeland, N. K. L., Griffin, R. E., Hernández Sandoval, B. E., Cherrington, E. A., Deval, C., & Hendy, T. (2025). Understanding Hydrological Responses to Land Use and Land Cover Change in the Belize River Watershed. Water (Switzerland), 17(13), 1–30. https://doi.org/10.3390/w17131915

Corona, J. A. I., Lakhankar, T., Pradhanang, S., & Khanbilvardi, R. (2014). Remote sensing and ground-based weather forcing data analysis for streamflow simulation. Hydrology, 1(1), 89–111. https://doi.org/10.3390/hydrology1010089

Daggupati, P., Pai, N., Ale, S., Douglas-Mankin, K. R., Zeckoski, R. W., Jeong, J., Parajuli, P. B., Saraswat, D., & Youssef, M. A. (2015). A recommended calibration and validation strategy for hydrologic and water quality models. Transactions of the ASABE, 58(6), 1705–1719. https://doi.org/10.13031/trans.58.10712

Darnianti, Rauf, A., Rahmawaty, Mulya, M. B., Delvian, & Rahmanta. (2026). Land cover dynamics and surface water quality conditions in the Upper Wampu Watershed, Indonesia. Asian Journal of Forestry, 10(1), 1–9. https://doi.org/10.13057/asianjfor/r100121

Edwards, P. J., Williard, K. W. J., & Schoonover, J. E. (2015). Fundamentals of Watershed Hydrology. Journal of Contemporary Water Research & Education, 154(1), 3–20. https://doi.org/10.1111/j.1936-704x.2015.03185.x

Faddillah, M., Yasmadi, Y., Endayanti, M., & Ginting, R. (2023). Analisa Hidrologi Kapasitas Bendung Wampu Kecamatan Kuta Buluh Kabupaten Karo Sumatera Utara. Jurnal Ilmiah Teknik Sipil, 12(2), 209. https://doi.org/10.46930/tekniksipil.v12i2.2704

François, M., de Aguiar, T. R., Mielke, M. S., Rousseau, A. N., Faria, D., & Mariano-Neto, E. (2024). Interactions Between Forest Cover and Watershed Hydrology: A Conceptual Meta-Analysis. Water (Switzerland), 16(23), 1–21. https://doi.org/10.3390/w16233350

Gay, E. T., Martin, K. L., & Caldwell, P. V. (2025). Projected land use changes will cause water quality degradation at drinking water intakes across a regional watershed. PLOS Water, 4(4 April), 1–21. https://doi.org/10.1371/journal.pwat.0000313

Grey, O. P., Webber, D. F. S. G., Setegn, S. G., & Melesse, A. M. (2014). Application of the soil and water assessment tool (SWAT model) on a small tropical island (Great River Watershed, Jamaica) as a tool in integrated watershed and coastal zone management. Revista de Biologia Tropical, 62, 293–305. https://doi.org/10.15517/rbt.v62i0.15924

Hatmoko, W., Levina, L., Radhika, R., Amirwandi, A., & Rendy, R. (2020).

Quantification of Environmental Flow Requirement for some Rivers in West Java. E3S Web of Conferences, 148. https://doi.org/10.1051/e3sconf/202014807003

Herawati, H., Suripin, & Suharyanto. (2015). Impact of climate change on streamflow in the tropical Lowland of Kapuas River, West Borneo, Indonesia. Procedia Engineering, 125, 185–192. https://doi.org/10.1016/j.proeng.2015.11.027

Heryani, N., Kartiwa, B., Sosiawan, H., Rejekiningrum, P., Adi, S. H., Apriyana, Y., Pramudia, A., Yufdy, M. P., Tafakresnanto, C., Rivaie, A. A., Suratman, Dariah, A., Malik, A., Yusuf, & Setiani, C. (2022). Analysis of Climate Change Impacts on Agricultural Water Availability in Cimanuk Watershed, Indonesia. Sustainability (Switzerland), 14(23), 1–18. https://doi.org/10.3390/su142316236

Hövel, A., Stumpp, C., Bogena, H., Lücke, A., Strauss, P., Blöschl, G., & Stockinger, M. (2024). Repeating patterns in runoff time series: A basis for exploring hydrologic similarity of precipitation and catchment wetness conditions. Journal of Hydrology, 629(November 2023). https://doi.org/10.1016/j.jhydrol.2023.130585

Kuntoro, A. A., Putro, A. W., Kusuma, M. S. B., & Natasaputra, S. (2017). The effect of land use change to maximum and minimum discharge in Cikapundung River Basin. AIP Conference Proceedings, 1903 (September 2015). https://doi.org/10.1063/1.5011621

Leta, M. K., Demissie, T. A., & Tränckner, J. (2021). Hydrological Responses of Watershed to Historical and Future Land Use Land Cover Change Dynamics of Nashe Watershed, Ethiopia. Water, 13(2372), 1–20. https://doi.org/10.3390/w13172372

Liou, Y. A., & Kar, S. K. (2014). Evapotranspiration estimation with remote sensing and various surface energy balance algorithms-a review. Energies, 7(5), 2821–2849. https://doi.org/10.3390/en7052821

Liu, T., Guo, Z., Li, X., Xiao, T., Liu, J., & Zhang, Y. (2024). Monitoring Water Quality Parameters Using Sentinel-2 Data: A Case Study in the Weihe River Basin (China). Sustainability, 16(16), 6881. https://doi.org/10.3390/su16166881

Lu, M., Rogiers, B., Beerten, K., Gedeon, M., & Huysmans, M. (2022). Exploring river-aquifer interactions and hydrological system response using baseflow separation, impulse response modeling, and time series analysis in three temperate lowland catchments. Hydrology and Earth System Sciences, 26(13), 3629–3649. https://doi.org/10.5194/hess-26-3629-2022

Montanari, L. (2006). Erratum: Investigation of dominant hydrological processes in a tropical catchment in a monsoonal climate via the downward approach (Hydrology and Earth System Science (2006) 10 (769-782)). Hydrology and Earth System Sciences, 10(6), 923–924. https://doi.org/10.5194/hess-10-923-2006

Nag, S., Roy, M. B., & Roy, P. K. (2024). Integrated hydrological modeling and water resource assessment in the Mayurakshi River Basin: A comprehensive study from historical data to future predictions. Geosystems and Geoenvironment, 3(4), 100308. https://doi.org/10.1016/j.geogeo.2024.100308

Narendra, B. H., Siregar, C. A., Dharmawan, I. W. S., Sukmana, A., Pratiwi, Pramono, I. B., Basuki, T. M., Nugroho, H. Y. S. H., Supangat, A. B., Purwanto, Setiawan, O., Nandini, R., Ulya, N. A., Arifanti, V. B., & Yuwati, T. W. (2021). A review on sustainability of watershed management in Indonesia. Sustainability (Switzerland), 13(19). https://doi.org/10.3390/su131911125

Ojha, S., Puri, L., Bist, S. P., Bastola, A. P., & Acharya, B. (2023). Watershed prioritization of Kailali district through morphometric parameters and landuse/landcover datasets using GIS. Heliyon, 9(6). https://doi.org/10.1016/j.heliyon.2023.e16489

Qian, J. H., Robertson, A. W., & Moron, V. (2010). Interactions among ENSO, the Monsoon, and Diurnal Cycle in Rainfall Variability over Java, Indonesia. Journal of the Atmospheric Sciences, 67(11), 3509–3524. https://doi.org/10.1175/2010JAS3348.1

Shekar, P. R., & Mathew, A. (2024). Morphometric analysis of watersheds: A comprehensive review of data sources, quality, and geospatial techniques. Watershed Ecology and the Environment, 6(December 2023), 13–25. https://doi.org/10.1016/j.wsee.2023.12.001

Sarigil, G., Cavus, Y., Aksoy, H., & Eris, E. (2024). Frequency curves of high and low flows in intermittent river basins for hydrological analysis and hydraulic design. Stochastic Environmental Research and Risk Assessment, 38(8), 3079–3092. https://doi.org/10.1007/s00477-024-02732-0

Shao, G., Zhang, D., Guan, Y., Sadat, M. A., & Huang, F. (2020). Application of different separation methods to investigate the baseflow characteristics of a semi-arid sandy area, Northwestern China. Water (Switzerland), 12(2), 1–22. https://doi.org/10.3390/w12020434

Supangat, A. B., Basuki, T. M., Indrajaya, Y., Setiawan, O., Wahyuningrum, N., Purwanto, Putra, P. B., Savitri, E., Indrawati, D. R., Auliyani, D., Nandini, R., Pramono, I. B., Nugroho, A. W., Wuryanta, A., Adi, R. N., Harjadi, B., Cahyono, S. A., Lastiantoro, C. Y., Handayani, W., … Anggraeni, I. (2023). Sustainable Management for Healthy and Productive Watersheds in Indonesia. Land, 12(11), 1–34. https://doi.org/10.3390/land12111963

Tang, J., Zhu, Y., Wei, Z., Feng, L., Yang, N., Sun, Z., & Luo, Q. (2021). Effectiveness of riparian vegetated filter strips in removing agricultural nonpoint source pollutants in agricultural runoff from the liao river area, China. Polish Journal of Environmental Studies, 30(5), 4709–4718. https://doi.org/10.15244/pjoes/133720

Twisa, S., Mwabumba, M., Kurian, M., & Buchroithner, M. F. (2020). Impact of land-use/land-cover change on drinking water ecosystem services in Wami River Basin, Tanzania. Resources, 9(4), 1–18. https://doi.org/10.3390/RESOURCES9040037

Verburg, P. H., Erb, K. H., Mertz, O., & Espindola, G. (2013). Land System Science: Between global challenges and local realities. Current Opinion in Environmental Sustainability, 5(5), 433–437. https://doi.org/10.1016/j.cosust.2013.08.001

Wang, D., Huang, G., Ding, H., Zhang, X., Wang, H., Zhang, Z., Li, D., & Zhao, J. (2023). Effects of Hydrological Season on the Relationship between Land Use and Surface Water Quality. Water, 15(13), 2351. https://doi.org/10.3390/w15132351

Yang, H., & Cao, J. (2021). Analysis of basin morphologic characteristics and their influence on the water yield of mountain watersheds upstream of the xiongan new area, north china. Water (Switzerland), 13(20). https://doi.org/10.3390/w13202903