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Analysis of the relationship between peak time of GR4J model and observed discharge: A case study of river basins (DAS) in Java Island

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Abstract: This study aims to improve the accuracy of the GR4J model in simulating the transformation of rainfall into discharge in ten watersheds on Java Island, which are representative of tropical climate conditions in developing countries. This study involves collecting daily rainfall and evapotranspiration data as model inputs, as well as observed discharge data for calibration and validation. The calibration process focuses on minimizing the error between predicted and observed discharge using the Nash-Sutcliffe Efficiency (NSE) and Relative Volume Error (RVE) metrics. The main focus of this study is to adjust the peak time parameter (X4) to match the observed peak discharge time (Tp). The results of the analysis show a significant correlation between the X4 values obtained by the model and the observed Tp, which allows the development of an adjustment formula in the GR4J model equation. This adjustment improves the accuracy of the unit hydrograph simulation both in shape and magnitude, allowing the model to better reflect realistic flow conditions. This study concludes that by adjusting the peak time parameter, the GR4J model can be optimized to provide more accurate discharge predictions in watersheds on Java Island. This increase in accuracy is expected to support more effective water resource planning and management in other regions of Indonesia.

Keywords: *Calibration model, GR4J model, Upper citarum watershed, Validation model, Water resources management.*

1. Introduction

River discharge data plays a very important role in designing flood control infrastructure. Accurate river discharge is needed to design an effective system to prevent flooding, considering that climate change that causes extreme rainfall is increasingly difficult to predict. However, the main problem that is often faced is the limited field river discharge data, which makes direct measurement difficult. In this context, one alternative that is often used is the use of rainfall data to estimate flood discharge, which of course requires conversion from rainfall to discharge.

Conversion of rainfall to discharge is done using a general flood equation that takes into account several factors, such as rainfall intensity, watershed area (DAS), and land cover characteristics in the area. These factors play an important role in determining how much water flow occurs after rain falls. In addition, the geographical and morphological conditions of an area also affect how water flows towards the river. Therefore, collecting accurate data on watershed conditions is very important in the conversion process so that the calculation of flood discharge becomes more realistic.

If rainfall data is not available, one solution is to use synthetic hydrograph analysis to estimate discharge. This method allows discharge estimation based on the physical and geographical characteristics of the watershed, such as area, river length, and slope gradient. Some synthetic hydrograph methods that are widely used in Indonesia for discharge estimation are the Snyder-Alexejev, SCS, Nakayasu, and HSS ITB methods. Each of these methods has a different approach and

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calculation, but all have the same goal, which is to provide an accurate picture of the potential flood discharge based on the characteristics of the existing watershed [1].

Unit hydrograph analysis produced by the GR4J model, developed by Perrin [2]. The GR4J model is one of the popular hydrological models used because of its effectiveness in producing discharge estimates with relatively few parameters. This model is a development of the previous model, namely GR3J [3]. The advantage of the GR4J model lies in its simplicity in calculation, but is still able to provide accurate results, so it is widely used in hydrological analysis to predict river flow in river basins (DAS) [4].

In this study, the analysis was conducted on ten watersheds in Java. The data used for model calibration consisted of daily rainfall data, potential evapotranspiration, and measured river discharge data at these locations. Daily rainfall and potential evapotranspiration were taken as the main inputs in the model, because these two factors directly affect water flow in the watershed. In addition, measured discharge data is also needed to calibrate the model, so that the discharge prediction results produced by the GR4J model are closer to the actual conditions in the field.

The GR4J model has been proven effective in providing accurate estimates, even with limited parameters, allowing the application of this model to various types of watersheds (DAS) with different characteristics. Therefore, this model is a very useful tool in designing flood control systems, especially in areas with limited field data. By using the GR4J model, hydrology practitioners can produce more accurate flood discharge predictions, which can then support better decision-making in water resource management and flood disaster mitigation [5].

One of the important areas to apply hydrological analysis is Java Island, which has unique geographical characteristics. The island stretches about 1,000 km from west to east with a maximum width of about 210 km, covering an area of 128,297 km^2. The presence of several active volcanoes that contribute to its landscape also plays a role in providing fertile soil, supporting agriculture in various regions, especially in the highlands. With such geographical conditions, the topography of Java Island is very diverse, ranging from lowlands to mountains, which affect the pattern of water flow in the area.

The geographical and demographic characteristics of densely populated Java, with more than 156 million people living on the island, add complexity to natural resource management, including flood control. Large cities such as Jakarta, Surabaya, Bandung, and Yogyakarta, which are economic and cultural centers, are often exposed to flood risks that can harm the economy [6]. The fertile volcanic soils of the Java highlands support productive agriculture, while the more tropical lowland areas influence the distribution of rainfall and river discharge. Therefore, it is important to apply accurate hydrological models, such as GR4J, to better predict and manage river discharge in these areas.

The main objective of this study is to optimize the GR4J model parameters by minimizing the deviation between the modeled and observed discharge. The modeling process is carried out in two stages: calibration and validation. The calibration stage uses daily data for eight years, while the validation stage uses data for the following eight years. The GR4J model is implemented using Matlab, with algorithms designed to optimize model parameters, compare modeled and observed discharge, and minimize deviations using the Nash-Sutcliffe Efficiency coefficient. This study aims to improve the accuracy of the GR4J model, so that it is more in accordance with the hydrograph observed in the Java watershed, especially in terms of peak discharge time and hydrograph shape.

2. Literature Review

In this study, several theories related to rainfall-runoff modeling and the use of the GR4J hydrological model will be used to explore the application and effectiveness of the model in predicting river flow, as well as its impact on water resources management and flood control [7]. The theories used will guide the analysis in this study to better understand how the GR4J model functions under varying conditions and faces challenges such as uncertainty in rainfall data, climate change, and model calibration [8]. By optimizing the application of the GR4J model in hydrological simulation and water resources management, especially in flood mitigation and more effective flood control planning.

2.1. Rainfall Data Uncertainty and Its Impact on Hydrological Models

One of the main theories underlying this research is the uncertainty of rainfall data that can affect the accuracy of the hydrological model. The quality of rainfall data in improving the efficiency of the hydrological model. Inaccuracies in rainfall data can cause significant variations in model parameters, which in turn affect the results of river flow simulations [9]. Therefore, this study will use this theory to understand how inaccurate rainfall data can affect the performance of the GR4J model in hydrological simulations.

2.2. The Impact of Climate Change on Flood Prediction

Another relevant theory is the impact of climate change on river flood prediction. Climate change has the potential to increase the frequency and intensity of floods in the future, making hydrological modeling increasingly important [10]. These changes affect the hydrological parameters used in models such as GR4J. This study will explore this theory by testing the extent to which the GR4J model is able to cope with the challenges posed by climate change, especially in predicting peak discharge and flood frequency.

2.3. Comparison of GR4J Model Performance with Other Models

In the existing literature, Comparison between GR4J and GR2M models, shows that GR4J has a slightly better performance in representing rainfall-runoff dynamics. This study will adopt this model comparison theory to assess the effectiveness of GR4J in a local context, as well as to understand how GR4J can be optimized through proper calibration to improve the accuracy of river flow prediction [11].

2.4. Model Calibration to Improve Simulation Accuracy

Integration of GR4J with wavelet-based artificial neural networks improves the accuracy of river flow prediction. This study will test the theory by calibrating GR4J using more accurate rainfall and river discharge data, and comparing its performance with field observations. The right calibration technique will be key to ensuring more accurate predictions, especially under variable hydrological conditions [12].

2.5. Use of the GR4J Model in Regions with Extreme Hydrological Characteristics

Various studies have shown that the GR4J model is very effective in various regions with different hydrological characteristics. The model works well in many regions, further calibration is needed, especially in regions with extreme hydrological conditions. Therefore, this study will test the application of GR4J in regions with diverse hydrological characteristics and provide recommendations for model calibration in areas with more extreme conditions [13].

2.6. Hybrid Approach in Rainfall-Runoff Modeling

A hybrid approach combining components from the IHACRES and GR4J models to improve the accuracy of rainfall-runoff predictions [14]. This theory shows that a combination of several models can overcome the limitations of each model and provide better simulation results. This study will test the potential of a hybrid approach in the context of the GR4J model to improve river flow prediction and flood control.

2.7. Advantages of the GR4J Model Compared to other Models

The GR4J model has been shown to be superior in representing hydrological processes compared to other models such as AWBM and Sacramento, as described in previous studies. Overall, this model has excellent performance in predicting river flow in various catchment areas. This study will adopt this theory to explore the advantages of GR4J in water resource management applications in areas with complex river flow characteristics [15].

3. Material and Methods

This study uses daily rainfall and river discharge data between 2008 and 2023. Rainfall data were collected from rainfall stations around the watershed, and discharge data were obtained from several measurement points. The GR4J model was used for modeling, calibrated with data from 2008 to 2015, and validated with data from 2016 to 2023. Calibration focused on adjusting four main parameters: X1 (groundwater reservoir capacity), X2 (exchange coefficient between groundwater and rivers), X3 (subsurface reservoir capacity), and X4 (transfer value), with the aim of minimizing prediction errors.

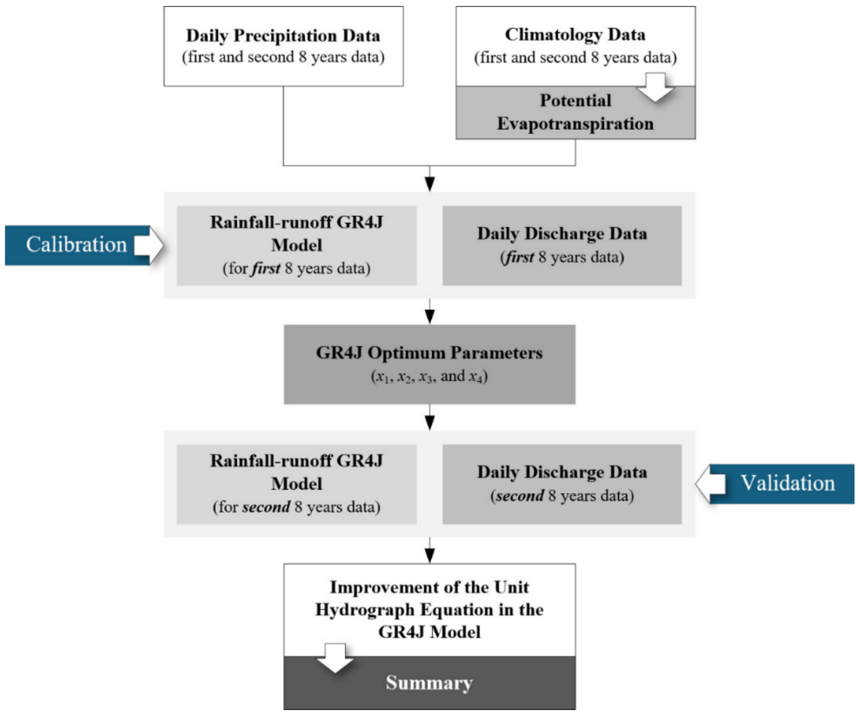

Figure 1.
Methodology in conducting this research.

Data processing and modeling were performed using MATLAB R2024a, where algorithms were applied to optimize the four parameters by minimizing the deviation between predicted and observed discharge [16]. This process aims to provide accurate discharge estimates for the Upper Citarum Watershed.

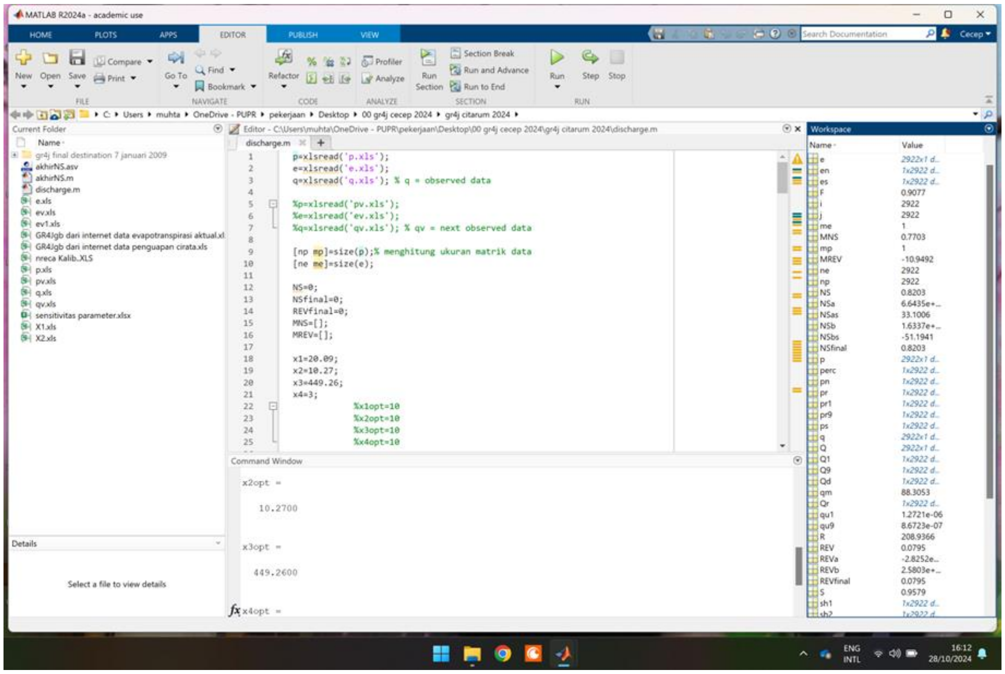

Figure 2.
GR4J Programming Interface in MATLAB R2024a.

The results showed that the optimum value obtained did not reach the Nash-Sutcliffe (NS) value of one or the Relative Volume Error (RVE) of zero, thus encouraging the use of sensitivity analysis. This analysis involves varying each parameter across its range to better understand its impact on model performance, with the resulting graph depicting the contribution of each parameter to the GR4J model.

3.1. GR4J Modeling Results

The GR4J model is a rainfall runoff model designed to optimize four main parameters: maximum production storage capacity (X1), groundwater exchange coefficient (X2), maximum runoff storage capacity (X3), and peak runoff time of the unit hydrograph (X4). According to Perrin [2] the GR4J model has better performance compared to other rainfall runoff models, such as the Tank, TOPMODEL, HBV, IHACRES, and SMAR models. This study covers 429 Watersheds (DAS) located in tropical and subtropical regions, which shows that the GR4J model is very suitable for application in Indonesia which has a tropical climate.

The GR4J model processes daily rainfall data into runoff through several stages. First, the maximum production storage capacity (X1) acts as a surface reservoir that captures rainfall. Soil type and porosity determine the capacity of this reservoir, with less permeable soils converting more rainfall into runoff. The second parameter, the soil water exchange coefficient (X2), indicates the exchange of groundwater within the runoff reservoir, where positive values indicate water inflow and negative values indicate water outflow. The third parameter, the maximum runoff storage capacity (X3), serves as a subsurface reservoir that stores water produced by percolation. Finally, the fourth parameter, peak runoff time (X4), measures the time it takes for runoff to reach its peak after rainfall begins.

Figure 3 shows the operational diagram of the GR4J model, with water volume expressed in millimeters (mm). The model uses daily rainfall (P) and evapotranspiration (E) data to calculate net rainfall (Pn) and net evapotranspiration (En). If P is greater than or equal to E, then Pn is equal to P minus E, and En is equal to zero. Conversely, if P is less than or equal to E, then En is equal to E minus P, and Pn is equal to zero.

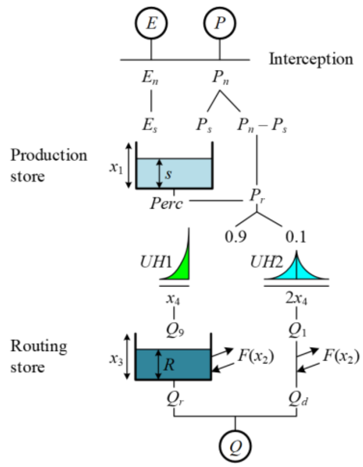

Figure 3.
GR4J rainfall-runoff model diagram [2].

The next step involves updating the production storage based on net rainfall. Percolation (Perc) is then calculated, which contributes to the route storage. The water entering the route storage is divided into fast flow (UH1) and slow flow (UH2), with 90% managed by UH1 and the remaining 10% by UH2. This arrangement allows the GR4J model to effectively represent both fast and slow hydrological processes.

GR4J model calibration and validation assist in the refinement of parameter values, ensuring the model provides a realistic representation of river flow under varying hydrological conditions. Accurate parameter tuning is critical to optimize the model's ability to predict discharge and capture runoff dynamics effectively [17].

To obtain the modeled discharge, this study uses Matlab R2024a software, where the program code is written using an algorithm as shown in Figure 4. The algorithm works by finding the optimal parameter value through an iterative process (looping) for each parameter, with an increase in a certain range.

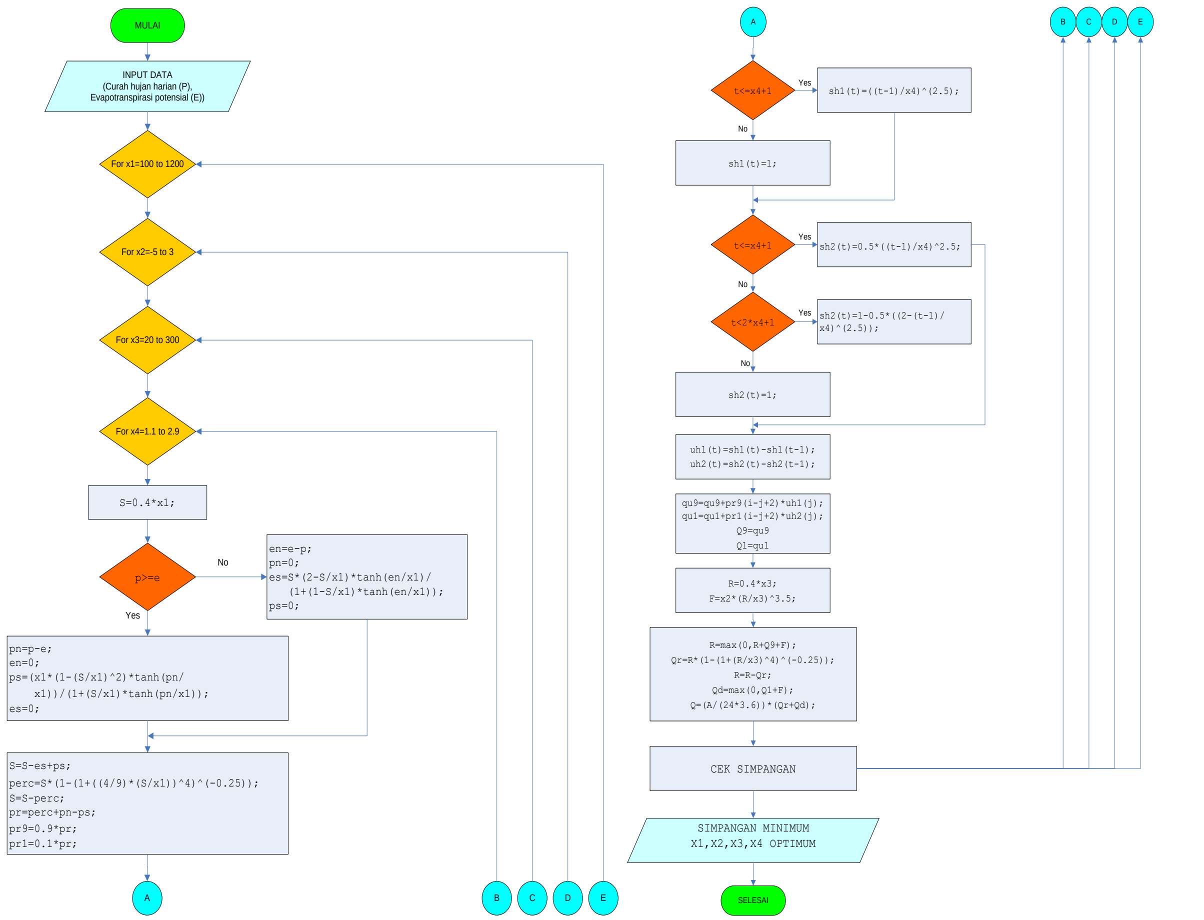

Figure 4.
GR4J rainfall-runoff model algorithm in MATHLAB R2024a.

3.2. Model Calibration

To calibrate the model and obtain optimal parameter values, daily discharge data at the watershed outlet were used. The error between the modeled and observed discharge was calculated using the Nash-Sutcliffe Efficiency (NSE) and Relative Volume Error (RVE) coefficients. The NSE method assesses the similarity between observed and modeled discharge, where a value of 1 indicates a perfect match.

$$NSE = 1 - \frac{\sum_{i-1}^{n}(X_i - Y_i)^2}{(X_i - \bar{X}_i)^2} \quad (1)$$

The NSE method assesses the similarity between observed and modeled discharge, with a maximum value of 1 indicating a perfect match.

Table 1.
Nash-Sutcliffe efficiency (NSE) value criteria.

***NSE*Mark**	**Interpretation**
NSE> 0.75	Good
0.36 < NSE < 0.75	Quality
NSE< 0.36	Not eligible

The general equation for relative volume error is stated as follows.

$$RVE = \frac{\sum(Q_{sim} - Q_{obs})}{\sum(Q_{obs})} \quad (2)$$

The median and 80% confidence intervals of the GR4J parameters are stated in Table 2 below.

Table 2.
Median model parameter values and 80% confidence intervals of estimates.

	Median value	80% confidence interval
X_1(unit of measurement)	350	100 – 1200
X_2(unit of measurement)	number 0	– 5 to 3
X_3(unit of measurement)	90	20 – 300
X_4(day)	1.7	1.1 – 2.9

4. Result and Discussion

4.1. Overview of the Research Site

The general equation for relative volume error was also used to evaluate model performance. Medians and approximately 80% confidence intervals for the GR4J model parameters are summarized in Table 2, which shows values for parameters X1, X2, X3, and X4, along with their respective ranges.

The calibration process is repeated to ensure optimal results. At each iteration, parameter values are adjusted to minimize prediction errors. If an iteration results in a smaller deviation than the previous value, the parameters are updated accordingly. If the deviation increases, the previous value is retained. This approach helps to fine-tune the model parameters to achieve better prediction accuracy in terms of discharge.

Table 3.
Optimum values of GR4J parameters and their deviations for Nanjung Station.

Coefficient		(2008 – 2015)		(Year 2016 – 2023)	
		NSE	*RVE*(%)	*NSE*	*RVE*(%)
X_1	462.76	0.82	0.07	0.65	32.38
X_2	3.34				
X_3	19.55				
X_4	1.23				

Table 3 shows the optimum values of GR4J parameters and their deviations for Nanjung Station in two different periods, namely 2008 to 2015 for calibration and 2016 to 2023 for validation. In the calibration period, the Nash-Sutcliffe efficiency coefficient (NSE) reached 0.82, while in the validation period it decreased to 0.65. This shows that the GR4J model provides quite good results in predicting river discharge in the calibration period, although there is a decrease in performance during validation. In addition, the RVE (Relative Volume Error) value in the calibration period is 0.07%, which indicates a very small deviation between the observed and modeled discharge. However, in the validation period, the RVE increases to 32.38%, indicating a greater discrepancy in predicting discharge in those years. Nevertheless, the results of this analysis still show that the GR4J model is effective for use in hydrological analysis in the studied area, especially in Java Island, with the potential for improvement through further calibration to increase prediction accuracy in newer periods [18]. Figure 5, which compares observed and modeled discharge, illustrates how optimized parameters can minimize the deviation between the two.

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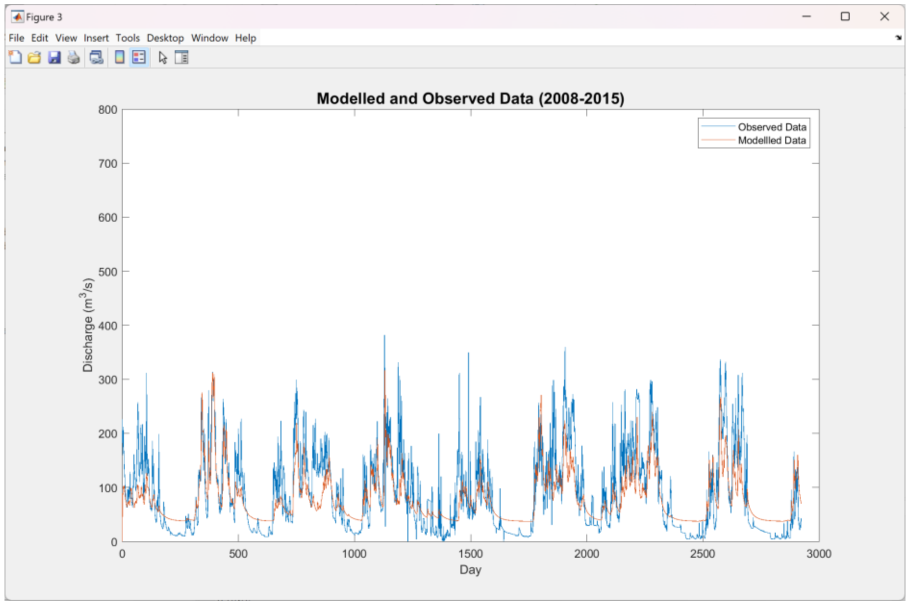

Figure 5.
Observed discharge vs modeled discharge (2008–2015).

The figure shows a comparison graph between the observed data and the modelled data for the period 2008-2015. The horizontal axis represents time in days, while the vertical axis shows discharge (in m^3/s). The graph depicts the pattern of daily discharge variation with significant fluctuations reflecting changes in water flow during the period. The modelled data is shown by the red line, while the observed data is shown by the blue line. Both datasets show similar general patterns, although there are minor differences at some points, which may indicate a discrepancy between the model results and the actual data. This plot helps analyze the accuracy of the model in replicating the observed data [19].

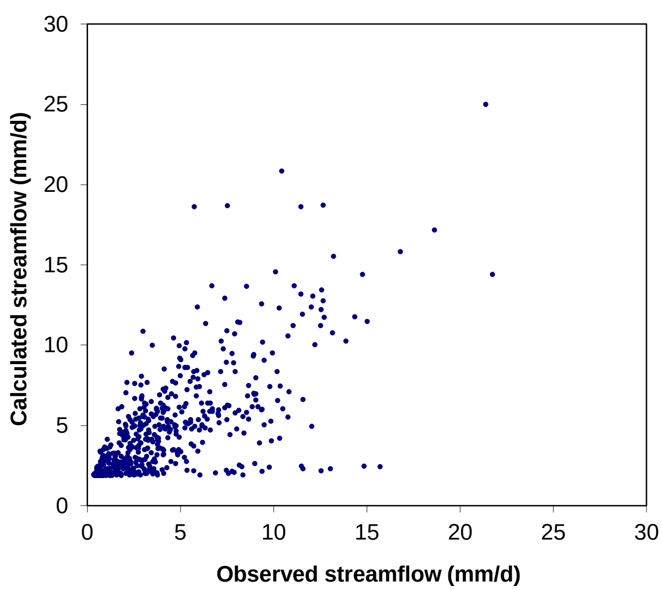

Figure 6.
XY streamflow plot comparing observed and modeled discharge (2008–2015).

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This figure is a scatter plot comparing the observed streamflow on the horizontal axis with the calculated or modeled streamflow on the vertical axis, both in mm/day. The graph shows the distribution of the data with most of the points concentrated near the origin (0,0), indicating that most of the flows are in the low range. This pattern of distribution of the points indicates a positive relationship between the observed and calculated data, where an increase in observed streamflow is generally followed by an increase in calculated flow [20]. However, there are deviations at some points, especially at high flow values, which may reflect the limitations of the model in predicting peak flows. This scatter plot is important to evaluate the performance of the model in replicating actual data.

To validate the model, the optimal parameters obtained from the previous modeling were applied to model data for the next eight years, from 2016 to 2023. Figure 7 compares the observed discharge with the modeled discharge using data from 2016 to 2023. These validation results further confirm the effectiveness of the GR4J model in capturing the hydrological dynamics that occur, as well as its ability to produce accurate predictions in the context of river basins in Indonesia.

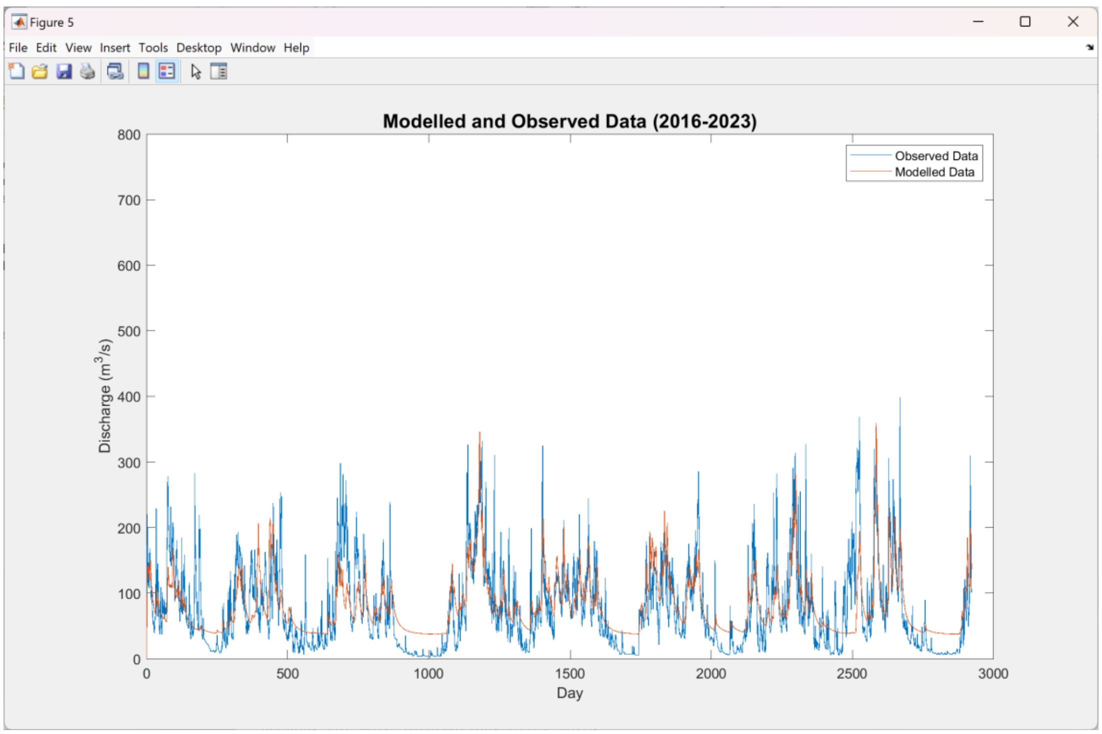

Figure 7.
Observed discharge vs modeled discharge (2016–2023).

This figure shows a comparison between the observed and modelled discharge data for the period 2016-2023. The horizontal axis represents time in days, while the vertical axis shows water discharge in m^3/s. The blue line represents the observed data, while the red line represents the modelled data. This graph shows the pattern agreement between the observed and modelled data, although there are small differences in some points. The similarity of this pattern indicates that the model used has the ability to replicate the actual data, although the model accuracy in this period seems to be slightly lower compared to the previous period (2008-2015), as can be seen from some more obvious deviations. This evaluation is important to assess the performance of the model in predicting streamflow under various hydrological conditions [21].

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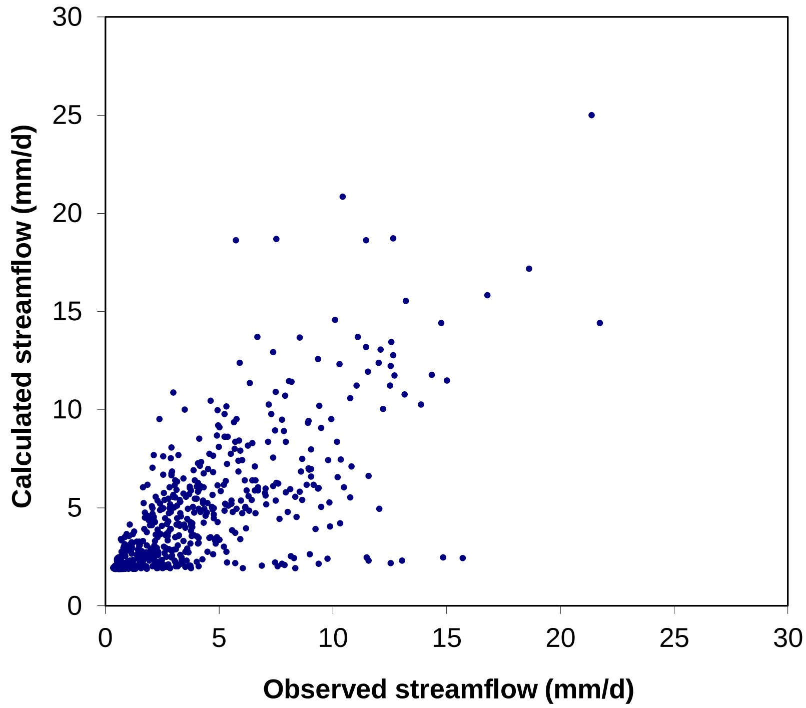

Figure 8.
XY streamflow plot comparing observed and modeled discharge (2016–2023).

A scatter plot graph with blue dots spread across a certain area. The horizontal (x) and vertical (y) axes have ranges that indicate the correlation or relationship between the two variables being measured. The density of dots in the lower left part of the graph indicates that much of the data is concentrated in areas with small x and y values, while the scattered dots in the upper right part indicate that there are some data with higher x and y values. This graph is used to identify patterns or trends in data, including linear, non-linear, or outlier relationships [21].

4.2. Peak Time Parameter Adjustment

To evaluate the agreement of the GR4J model with actual field conditions, the X4 parameter, which represents the peak time, was compared with the average value obtained from the actual hydrographs recorded by each Automatic Water Level Recorder (AWLR). More than 100 hydrographs were analyzed, ensuring that they met the criteria for a complete cycle. The average peak time (Tp) of these hydrographs was 6.85 hours. Normal distribution analysis showed that the Tp values ranged from 5.85 to 7.85 hours, with a probability of 68.26%, indicating that most values were within this range. The average Tp was consistent for the Upper Citarum Watershed, with similar calculations applied to other watersheds in Java Island.

Table 4.
Optimum values of GR4J parameters and their deviations.

No.	Watershed	Area (km^2)	*NS*	*RVE*	X_1 (unit of measurement)	X_2(unit of measurement)	X_3(unit of measurement)	X_4(day)	*But*(O'clock)
1	Cibeka	434.06	0.63	2.88E-06	2797.63	1.90	76.87	1.01	6.47
2	Cukangleus	552.85	0.64	-4.60E-08	515.55	13.99	71.91	1.12	7.05
3	Cimuntur	621.00	0.71	-9.14E-08	913.98	2.89	20.37	1.14	6.72
4	Guy	241.96	0.47	-1.44E-06	1652.43	2.04	10.35	1.09	3.54
5	Girimargo	104.61	0.39	1.19E-07	466.38	3.19	38.81	1.93	3.28
6	The Longhorn	70.45	0.36	-4.06E-08	1409.51	1.75	6.81	0.50	3.12
7	Majalaya language	204.62	0.53	-3.85E-07	1352.89	4.12	at 33.30	1.07	4.74
8	R Complex	111.19	0.50	2.30E-08	35.63	33.69	86.14	0.99	4.86
9	Old Fashioned	1350.14	0.73	5.99E-08	1339.43	3.78	14.46	1.27	4.98
10	South	1756.42	0.82	-6.99E-02	462.76	3.34	19.55	1.23	6.73

This table shows the optimum values of GR4J parameters and their deviations for different watersheds. Each watershed has a different size, ranging from 70.45 km^2 to 1756.42 km^2. The Nash-Sutcliffe (NS) value and relative volume error (RVE) provide an idea of how well the model fits the observed data in each watershed. The GR4J model parameters including X1, X2, X3, X4, and Tp each show different values in each watershed, which are related to the various physical and climatic characteristics of the area [20]. In the Cibeka watershed with an area of 434.06 km^2, the NS value is 0.63 and the RVE is 2.88E-06, indicating relatively good accuracy in river discharge modeling. On the other hand, in the smaller Guwo watershed with an area of 241.96 km^2, the NS value is lower at 0.47 and the RVE is -1.44E-06, indicating a larger deviation between the model and observation data. This indicates that the GR4J model results are more accurate in watersheds with certain conditions, while in other areas there may be higher prediction errors [22]. Deviation of GR4J parameter values (such as X1, X2, X3, X4, and Tp) shows significant variation between regions. For example, X1 in Cibeka Watershed has a value of 2797.63, while in Dayeuh Kolot Watershed it reaches 1339.43, reflecting differences in river flow characteristics and responses to model parameters. The Tp parameter, which describes the peak time, also varies between 3.12 hours in Jenglong Watershed to 7.05 hours in Cukangleus Watershed, indicating differences in river flow response time to rainfall in each region. The differences in these values reflect the importance of adjusting the GR4J parameters appropriately for each watershed. The optimum values obtained from model calibration and validation can help improve future hydrological predictions, which are very important for water resource management planning and natural disaster mitigation such as floods [23]. However, the variation in these values also confirms that model accuracy can be influenced by local factors specific to each watershed.

The modeling results show a difference between the modeled Tp value and the actual Tp value obtained from the observed hydrograph. Figure 9 illustrates the relationship between the X4 parameter and the observed Tp value.

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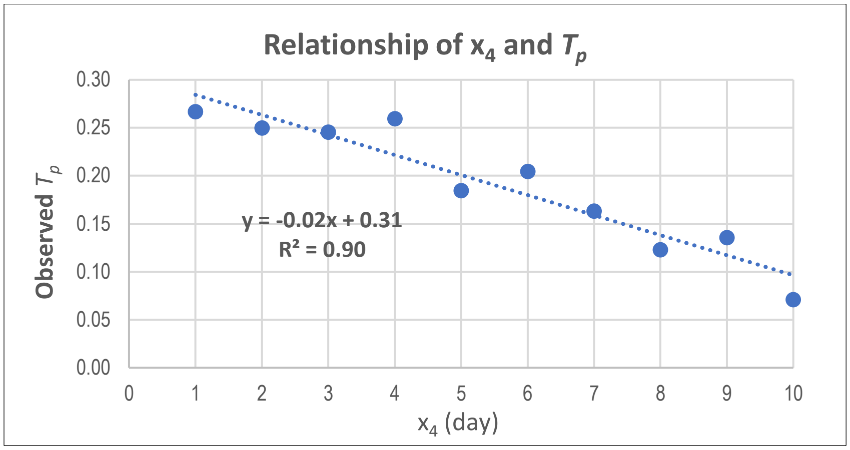

Figure 9.
Relationship between x4 and actual peak time average.

There is a significant relationship between the difference in Tp from the modeling results and the observed Tp, which is expressed as $y = -0.02x + 0.31$. This relationship facilitates the adjustment of the general GR4J modeling equation for the unit hydrograph.

4.3. Unit Hydrograph Adjustment

After determining the peak time adjustment equation, the next step is to adjust the hydrograph shape so that it can accurately describe the watershed unit hydrograph. According to Soemarto [24] the S curve is a direct runoff hydrograph resulting from continuous rainfall with constant intensity and unlimited duration.

The S-curve for a watershed can be obtained from its unit hydrograph over a given period. Continuous rainfall consists of an infinite series of rainfall events, each of constant intensity for a given duration. Thus, the effect of continuous rainfall can be represented by summing the ordinates of an infinite series of hydrographs, each shifted by one period.

To convert a unit hydrograph of duration t1 to a unit hydrograph of a different duration t2, the S-Curve method is used. The conversion is achieved by plotting an S-Curve based on the original unit hydrograph (referred to as S-Curve) and then plotting another S-Curve (S-Curve) shifted t2 hours to the right. The difference in ordinates between S-Curve and S-Curve at any point corresponds to the ordinate of the unit hydrograph for duration t2, where its height is expressed as (t1/t2)d, where d represents the height of the unit hydrograph for duration t1.

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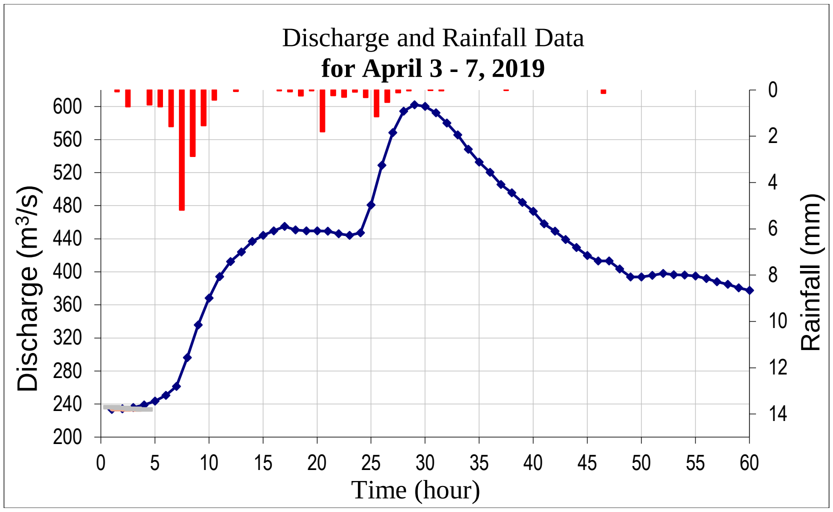

Figure 10.
Rainfall and Water Discharge in the Upper Citarum River Basin (DAS).

From the rainfall events that occurred between April 3 and April 7, 2019, five different hydrographs were generated. Baseflow was subtracted from each hydrograph to isolate the contribution of each rainfall event. The following figure illustrates the five rainfall events after baseflow adjustment.

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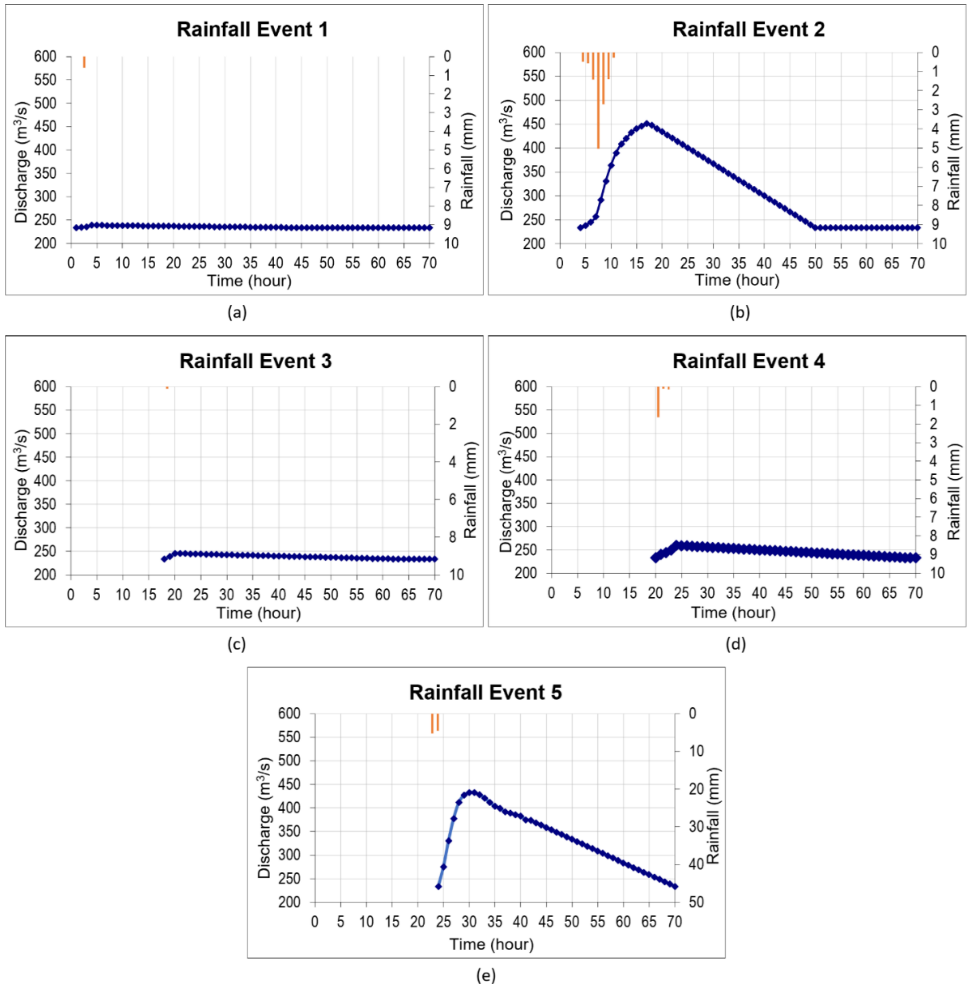

Figure 11.
Rainfall Event 1 – Rainfall Event 5.

Of the five separate rainfall events, the fifth event was selected for unit hydrograph analysis because of its characteristics that are representative of the hydrological response of the watershed in general. The effective rainfall recorded during this event occurred over three-time intervals of three hours each, with effective rainfall intensities of 0.17 mm, 1.01 mm, and 0.39 mm. These data were used to analyze the relationship between effective rainfall and the resulting surface runoff. The hydrograph generated from this event was then developed into a unit hydrograph, which is a representation of the runoff due to a 1 mm rainfall evenly distributed across the watershed. This unit hydrograph provides an overview of the hydrological behavior of the watershed to rainfall and is very useful for predicting runoff from other rainfall events. To refine and improve the unit hydrograph, the S-Curve method was used. This method allows for a more detailed analysis by integrating the runoff discharge values so that it can describe the cumulative runoff over a longer period of time. The resulting S-Curve hydrograph reflects the capacity of the watershed to respond to overall rainfall and provides an effective tool for applications in water resources planning, flood mitigation, and watershed management. This method also helps in ensuring that the resulting watershed hydrological response is accurate and consistent with field conditions.

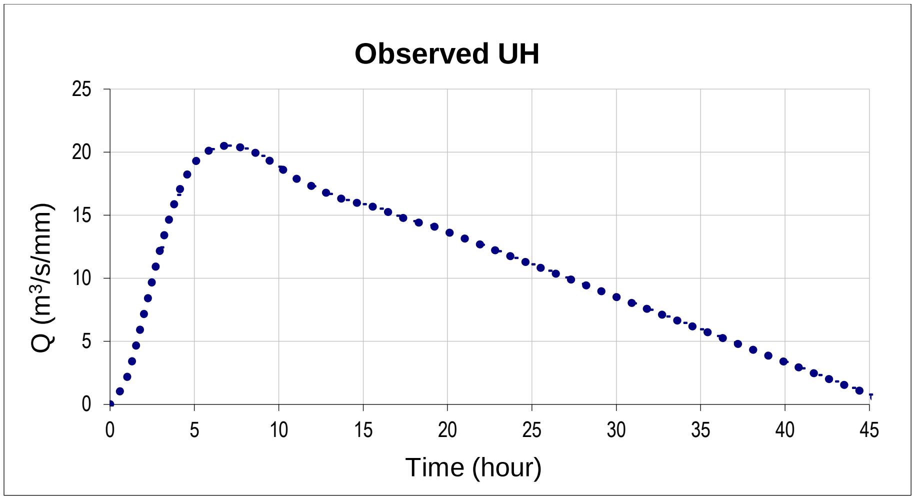

Figure 12.
Unit hydrograph observed in the Upper Citarum Watershed.

Figure 12 presents the observed unit hydrograph for the Upper Citarum River Basin, with a volume under the curve of 1,756,421 m^3 and a rainfall depth of 1 mm. This unit hydrograph reflects the characteristics of the watershed and can be used as a reference to adjust the unit hydrograph generated by the GR4J model. In particular, the shape of the observed unit hydrograph differs significantly from that generated by the GR4J model, which is generally triangular. This difference indicates the need to adjust the unit hydrograph equation of the GR4J model to better align with the observed data. Such adjustment is essential to improve the accuracy of the model in representing river flow dynamics, so that the GR4J model is more effective for water resources analysis, including flood planning and flood risk management.

In order to produce a hydrograph that closely matches the desired curve, a fitting method is applied. This approach modifies the model output to better match the observed data, resulting in more representative results. As a result, new equations (7) and (8) are derived, which provide a more precise relationship between the variables involved. This fitting serves as a basis for further hydrological analysis and evaluation. Figure 13 illustrates the fitted unit hydrograph obtained from the GR4J model, which has been modified to approximate the observed hydrograph shape.

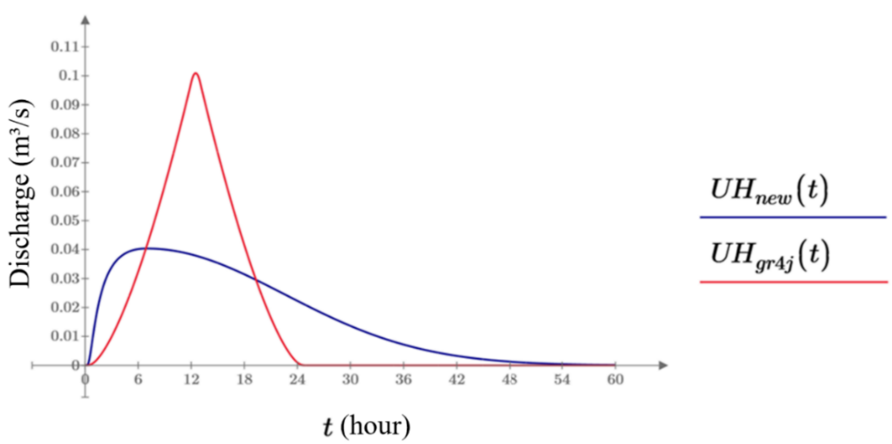

Figure 13.
Modified GR4J UH vs UH modeling in the Upper Citarum Watershed.

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4.4. Unit Hydrograph Adjustment Procedure

This procedure outlines the steps required to modify the unit hydrograph obtained from GR4J modeling to better align with the observed unit hydrograph.

(1) X_4obtained from the GR4J modeling results.
(2) The relationship between X4 and the observed peak time is y = –0.02x + 0.31.
(3) To obtain unit hydrographs (UH) from GR4J modelling [2]

$$For\ 0 < t < X_4, SH_{GR4J} = \frac{1}{2}\left(\frac{t}{X_4}\right)^{\frac{5}{2}} \quad (4)$$

$$For\ 0 < t < 2X_4, SH_{GR4J} = 1 - \frac{1}{2}\left(2 - \frac{t}{X_4}\right)^{\frac{5}{2}} \quad (5)$$

$$UH_{GR4J}(t) = SH_{GR4J}(t) - SH_{GR4J}(t-1) \quad (6)$$

(4) To get a new UH that is in Indonesian.

$$For\ t \leq T_p \rightarrow y(t) = 10^{\left(\frac{-1}{\left(\frac{t}{T_p}\right)}\left(1-\left(\frac{t}{T_p}\right)\right)\right)^2} \quad (7)$$

$$For\ t > T_p \rightarrow y(t) = 10^{\left((-0.0431)\left[1-\left(\frac{t}{T_p}\right)\right]\right)^2} \quad (8)$$

To get discharge during floods,

$$Q_p = \frac{\frac{A_{DAS}}{35.9T_p}}{3600} \quad (9)$$

To develop new UH,

$$Q(t) = y(t) \bullet Q_p \quad (10)$$

$$A_{HSS} = \sum_{t-1}^{n} Q(t) \quad (11)$$

$$UH_{new}(t) = \frac{Q(t)}{A_{HSS}} \quad (12)$$

From this adjusted unit hydrograph, a design flood hydrograph can be generated for a given recurrence interval. This section presents examples of designed flood hydrographs for the Upper Citarum watershed, corresponding to 5-year, 20-year, and 25-year recurrence intervals. The recurrence interval discharge is calculated based on sorted statistical data to obtain the probability of peak discharge occurring for the specified interval.

This flood hydrograph is created using the following equation after the planned discharge value for a particular year is determined:

$$Q_{5yr} = 520m/s$$

$$UH_{5yr}(t) = UH_{new}(t)\frac{Q_{5yr}(t)A_{HSS}}{Q_p} \quad (13)$$

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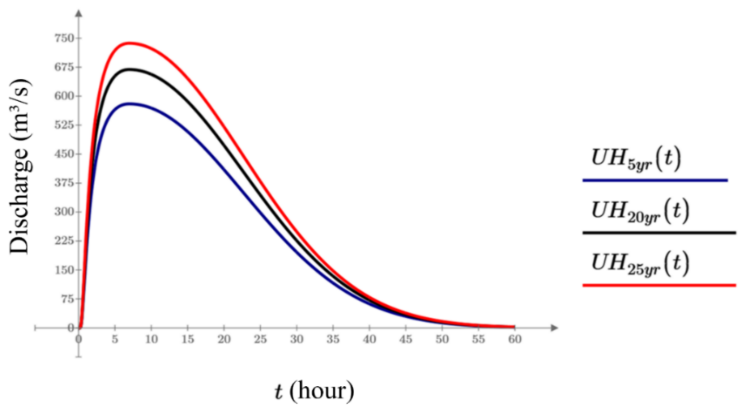

Figure 14.
Hydrographs with flow recurrence intervals of 5, 20, and 25 years.

Figure 14 shows the hydrographs generated with recurrence intervals of 5, 20, and 25 years, which show very similar results to the observed hydrographs obtained from the previous unit hydrograph analysis. The high agreement between the hydrographs generated by the GR4J model and the observational data strengthens the evidence that this model is reliable for predicting river flows under flood scenarios with a reasonable degree of accuracy [23]. This reflects the model's ability to represent river flow characteristics realistically despite variations in flow scenarios based on different time intervals. In addition, the results of this study indicate that adjustments to the unit hydrograph can improve the model's ability to describe river flow behavior more accurately [25]. This adjustment allows the model to reflect changes in flood flow intensity and duration that are more in line with field conditions. This aspect is critical for effective water resources management, where a proper understanding of river flows can assist in flood risk mitigation planning [23].

By using design hydrographs based on analyzed data, hydrologists can make more informed, evidence-based decisions in planning flood prevention and mitigation measures [22]. With more accurate information about possible peak discharges and flow durations, infrastructure planning, such as flood control, dam construction, and drainage system design, can be done more efficiently [26]. Therefore, the application of the GR4J model in this hydrograph design scenario not only contributes to improving the accuracy of hydrological forecasting, but also supports better flood risk management and data-based decision making for environmental sustainability and public safety [27].

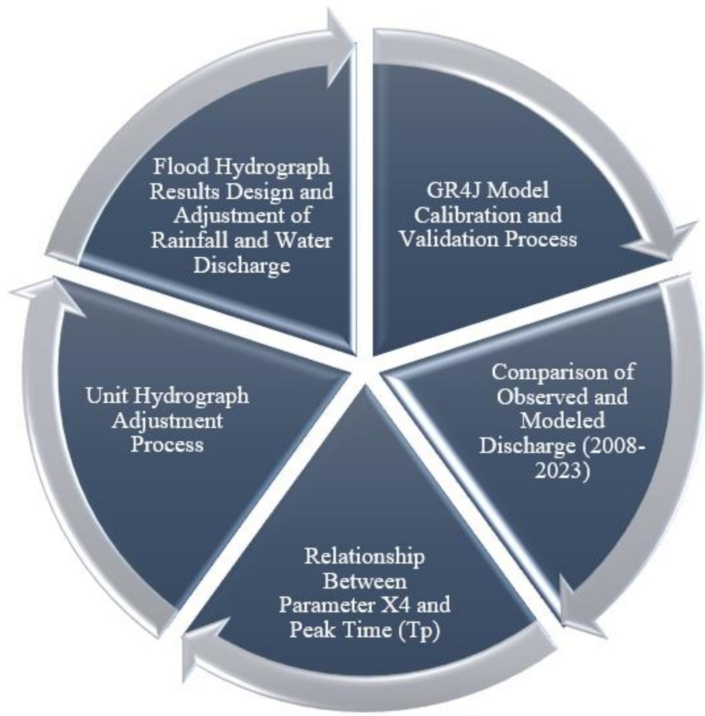

Figure 15.
Peak Time Relationship Model of GR4J Model.

The above pattern of development of findings and novelty resulting from this study, important findings resulting from this study, which not only improve the understanding of the GR4J model, but also contribute to the development of more accurate unit hydrograph adjustment methods and flood hydrograph design.

1. GR4J Model Calibration and Validation Process. In this study, the GR4J model calibration and validation process was carried out in two different time periods, namely 2008-2015 for calibration and 2016-2023 for validation. During the calibration process, model parameters were adjusted by optimizing the relative volume error (RVE) and Nash-Sutcliffe efficiency (NSE) to improve the accuracy of model predictions. In the validation stage, the parameters obtained from the calibration were used to predict river discharge in a more recent period and compared with observational data. The novelty found was the application of an iterative calibration and validation process aimed at improving model accuracy, as well as evaluation using two different time periods.
2. Comparison of Observed and Modeled Discharge (2008-2023). The comparison chart of observed and modeled discharge shows how the GR4J model results compare to the observed data in two time periods, 2008-2015 and 2016-2023. The graph shows the agreement between observed and modeled discharge, as well as the deviations that occurred during validation. The decrease in the efficiency of the GR4J model in the validation period indicates that the model is not always able to accurately predict river discharge under certain conditions. The novelty of this finding is the analysis of the differences between observed and modeled discharge in two different time periods, which provides deeper insight into the weaknesses of the model in certain periods.
3. Relationship Between X4 Parameters and Peak Time (Tp). This study also identified a mathematical relationship between the modeled X4 parameters and the observed peak time (Tp). The resulting graphs show how these parameters can be used to adjust the peak time in the GR4J model to better reflect field data. The application of this mathematical relationship allows for better adjustment of the peak time, so that the GR4J model can produce more accurate

predictions. The novelty found is the use of mathematical relationships for peak time adjustment in the GR4J model, as well as the implementation of this adjustment in unit hydrograph modeling.

4. Unit Hydrograph Adjustment Process. The adjustment of the GR4J unit hydrograph for a particular watershed is carried out through three main steps: first, determining the unit hydrograph from the GR4J modeling; second, using the adjustment equation to obtain a more accurate unit hydrograph; and third, generating a design flood hydrograph. This adjustment process is important to ensure that the GR4J model can better match the observed data. The novelty in this study is the application of the S-Curve method for unit hydrograph adjustment, as well as the development of a design flood hydrograph based on certain recurrence intervals (e.g., 5, 20, and 25 years), which is useful for infrastructure planning and flood risk mitigation.
5. Design Flood Hydrograph Results and Rainfall and Water Discharge Adjustment. In this study, the design flood hydrograph was calculated with different recurrent flow intervals (5, 20, and 25 years), and the results were compared with the observed and modeled discharges. In addition, an analysis was also conducted on the relationship between rainfall and water discharge in the Upper Citarum Watershed, using five rainfall events to develop a unit hydrograph. The novelty found is the effective use of rainfall data in developing a more representative unit hydrograph, as well as the application of the S-Curve method for cumulative runoff analysis over a longer period. This provides more accurate insights in designing the design flood hydrograph for better infrastructure planning.

5. Conclusion

The results of this study lead to several key conclusions. The GR4J model has proven to be effective.as a rainfall-runoff modeling tool that can predict discharge by utilizing four independent variables. One of the key parameters produced by this model is X4, which is the peak flood time (Tp). The calibration results show that the Nash-Sutcliffe (NSE) value reaches 0.82 for the calibration data and 0.65 for the validation data, indicating that this model performs well in estimating discharge. However, in the case study in Java, there is a difference between the modeled and observed peak times. This indicates the need for adjustments to align the modeled Tp with the observed Tp more accurately. A relationship is found between the modeled Tp and the observed Tp, which is expressed in the equation$y = -0.02x + 0.31$, with Tp measured in days. The GR4J model has been proven to be effective in hydrological analysis, especially in the studied areas, such as the Citarum region. Nevertheless, the comparison between observed and modeled discharge shows good agreement, although further adjustments are still needed to improve the prediction accuracy.

Based on the results of this study, there are several suggestions for further research. First, the scope of the study can be expanded by involving more watersheds, especially outside Java, to obtain a more general picture and capture the diversity of characteristics in various watersheds. This study is limited by the availability of data that only covers 10 watersheds in Java. Furthermore, the focus of the study can be expanded to natural river systems to ensure that the observation data reflects the true characteristics of the watershed without being influenced by artificial modifications in water discharge. This will help produce more accurate and relevant models to real conditions. Finally, it is recommended to develop a more comprehensive methodology in data collection and analysis, including the use of modern monitoring technology that can provide more accurate data on rainfall and water discharge.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Author's Contribution:

All authors contributed to the study. CM conceived the study, performed calculations, and analyzed data. SWD and DH supervised the work, provided guidance, and reviewed the results. CM drafted the manuscript. All authors read and approved the final manuscript.

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References

[1] Z. Yu, J. Wu, H. Yao, X. Chen, and Y. Cai, "Calibrating a hydrological model in ungauged small river basins of the northeastern Tibetan Plateau based on near-infrared images," *Journal of Hydrology*, vol. 618, p. 129158, 2023. https://doi.org/10.1016/j.jhydrol.2023.129158

[2] C. Perrin, *The GR4J model: A daily lumped rainfall–runoff model*. France: Cemagref, Lyon, 2003.

[3] S. Golian, C. Murphy, and H. Meresa, "Regionalization of hydrological models for flow estimation in ungauged catchments in Ireland," *Journal of Hydrology: Regional Studies*, vol. 36, p. 100859, 2021. https://doi.org/10.1016/j.ejrh.2021.100859

[4] R. Tang, Z. Dai, X. Mei, and Y. Lou, "Joint impacts of dams and floodplain on the rainfall-induced extreme flood in the Changjiang (Yangtze) River," *Journal of Hydrology*, vol. 627, p. 130428, 2023. https://doi.org/10.1016/j.jhydrol.2023.130428

[5] T. Cornelissen, B. Diekkrüger, and S. Giertz, "A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment," *Journal of Hydrology*, vol. 498, pp. 221-236, 2013. https://doi.org/10.1016/j.jhydrol.2013.06.016

[6] L. Gu *et al.*, "How well do the multi-satellite and atmospheric reanalysis products perform in hydrological modelling," *Journal of Hydrology*, vol. 617, p. 128920, 2023. https://doi.org/10.1016/j.jhydrol.2022.128920

[7] M. Bednář and D. Marton, "Developing a lumped rainfall-runoff model in daily timestep for the Central European regions: A case study of the Czech Republic," *Environmental Modelling & Software*, vol. 179, p. 106092, 2024. https://doi.org/10.1016/j.envsoft.2024.106092

[8] F. Moussu, L. Oudin, V. Plagnes, A. Mangin, and H. Bendjoudi, "A multi-objective calibration framework for rainfall–discharge models applied to karst systems," *Journal of Hydrology*, vol. 400, no. 3-4, pp. 364-376, 2011. https://doi.org/10.1016/j.jhydrol.2011.01.047

[9] C. Xu *et al.*, "A hybrid model coupling process-driven and data-driven models for improved real-time flood forecasting," *Journal of Hydrology*, vol. 638, p. 131494, 2024. https://doi.org/10.1016/j.jhydrol.2024.131494

[10] S. Nemri and C. Kinnard, "Comparing calibration strategies of a conceptual snow hydrology model and their impact on model performance and parameter identifiability," *Journal of Hydrology*, vol. 582, p. 124474, 2020. https://doi.org/10.1016/j.jhydrol.2019.124474

[11] E. Cantoni *et al.*, "Hydrological performance of the ERA5 reanalysis for flood modeling in Tunisia with the LISFLOOD and GR4J models," *Journal of Hydrology: Regional Studies*, vol. 42, p. 101169, 2022. https://doi.org/10.1016/j.ejrh.2022.101169

[12] L. Kong-A-Siou, P. Fleury, A. Johannet, V. B. Estupina, S. Pistre, and N. Dörfliger, "Performance and complementarity of two systemic models (reservoir and neural networks) used to simulate spring discharge and piezometry for a karst aquifer," *Journal of Hydrology*, vol. 519, pp. 3178-3192, 2014. https://doi.org/10.1016/j.jhydrol.2014.10.041

[13] S. X. N. Mejía, S. M. Paz, H. Tabari, and P. Willems, "Climate change impacts on hydrometeorological and river hydrological extremes in Quito, Ecuador," *Journal of Hydrology: Regional Studies*, vol. 49, p. 101522, 2023. https://doi.org/10.1016/j.ejrh.2023.101522

[14] P. M. Ndiaye, A. Bodian, A. Dezetter, A. Ogilvie, and O. Goudiaby, "Sensitivity of global hydrological models to potential evapotranspiration estimation methods in the Senegal River Basin (West Africa)," *Journal of Hydrology: Regional Studies*, vol. 53, p. 101823, 2024. https://doi.org/10.1016/j.ejrh.2024.101823

[15] P. Badika, A. S. Raghuvanshi, and A. Agarwal, "Climate change impact assessment on the hydrological response of the Tawa basin for sustainable water management," *Groundwater for Sustainable Development*, vol. 26, p. 101249, 2024. https://doi.org/10.1016/j.gsd.2024.101249

[16] M. A. Faiz *et al*., "Performance evaluation of hydrological models using ensemble of General Circulation Models in the northeastern China," *Journal of Hydrology*, vol. 565, pp. 599-613, 2018. https://doi.org/10.1016/j.jhydrol.2018.08.057
[17] J. M. Andrade, A. R. Neto, R. L. Nóbrega, M. A. Rico-Ramirez, and S. M. Montenegro, "Efficiency of global precipitation datasets in tropical and subtropical catchments revealed by large sampling hydrological modelling," *Journal of Hydrology*, vol. 633, p. 131016, 2024. https://doi.org/10.1016/j.jhydrol.2024.131016
[18] C. Ollivier *et al*., "Karst recharge-discharge semi distributed model to assess spatial variability of flows," *Science of the Total Environment*, vol. 703, p. 134368, 2020. https://doi.org/10.1016/j.scitotenv.2019.134368
[19] E. Ergün and M. C. Demirel, "On the use of distributed hydrologic model for filling large gaps at different parts of the streamflow data," *Engineering Science and Technology, an International Journal*, vol. 37, p. 101321, 2023. https://doi.org/10.1016/j.jestch.2022.101321
[20] M. Abdallah *et al*., "Hydrological insights: Comparative analysis of gridded potential evapotranspiration products for hydrological simulations and drought assessment," *Journal of Hydrology: Regional Studies*, vol. 57, p. 102113, 2025. https://doi.org/10.1016/j.ejrh.2024.102113
[21] J. Cairns, M. Mason, A. Harrison, F. Johnson, A. Davie, and W. Glamore, "Mining impacts peatland hydrology reducing discharge and water storage volumes," *Journal of Hydrology*, vol. 640, p. 131735, 2024. https://doi.org/10.1016/j.jhydrol.2024.131735
[22] C. Sezen, N. Bezak, Y. Bai, and M. Šraj, "Hydrological modelling of karst catchment using lumped conceptual and data mining models," *Journal of Hydrology*, vol. 576, pp. 98-110, 2019. https://doi.org/10.1016/j.jhydrol.2019.06.036
[23] J. Yang, F. Chen, A. Long, H. Sun, C. He, and B. Liu, "Runoff simulation of the Kaidu River Basin based on the GR4J-6 and GR4J-6-LSTM models," *Journal of Hydrology: Regional Studies*, vol. 56, p. 102034, 2024. https://doi.org/10.1016/j.ejrh.2024.102034
[24] C. D. Soemarto, *Hydrology: An introduction to hydrologic science*. Jakarta, Indonesia: Erlangga, 1995.
[25] N. Karki, N. M. Shakya, V. P. Pandey, L. P. Devkota, A. M. S. Pradhan, and S. Lamichhane, "Comparative performance of regionalization methods for model parameterization in ungauged Himalayan watersheds," *Journal of Hydrology: Regional Studies*, vol. 47, p. 101359, 2023. https://doi.org/10.1016/j.ejrh.2023.101359
[26] I. Fustos, R. Abarca-del-Rio, O. Artal, F. Alvial, and H. Sepulveda, "Impact on discharge modelling using different spatial and temporal resolution scenarios in South of Chile," *Journal of South American Earth Sciences*, vol. 115, p. 103727, 2022. https://doi.org/10.1016/j.jsames.2022.103727
[27] B. Juma, L. O. Olang, M. A. Hassan, J. Mulligan, and P. M. Shiundu, "Simulation of flood peak discharges and volumes for flood risk management in the ungauged urban informal settlement of Kibera, Kenya," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 128, p. 103236, 2022. https://doi.org/10.1016/j.pce.2022.103236