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THE TRMM RAINFALL-RUNOFF TRANSFORMATION MODEL USING GR4J AS A PREDICTION OF THE TUGU DAM RESERVOIR INFLOW

* Mohamad Bagus Ansori[1], Nadjadji Anwar[1]

[1]Faculty of Civil, Planning and Geo-Engineering, Institut Teknologi Sepuluh Nopember, Indonesia

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ABSTRACT: This study presents numerical modeling to simulate the rainfall-runoff model using Génie Rural à 4 paramètres Journalier (GR4J) of the Keser Watershed (East Java, Indonesia) to predict the reservoir inflow of the Tugu dam. The four independent parameters used to optimize the daily rainfall-runoff model are the maximum capacity of the production store (X_1), the underground water exchange coefficient for the catchment (X_2), the one-day capacity of the routing storage (X_3), and the time base of the unit hydrograph (X_4). The TRMM daily precipitation satellite time series is used as the rainfall input data spanning two years (2017-2018). Furthermore, the potential evapotranspiration for the catchment was calculated using the Penman method. The rainfall-runoff transformation results of the discharge simulation were then compared with observed discharge data collected from the hydrometry gauge station. The simulation results showed that the best performances of the model obtain 7.85, 2.52, 3.93, and -1.35 for the coefficient result of the maximum capacity of the production store (X_1), the underground water exchange coefficient (X_2), the one-day capacity of the routing storage (X_3), and time base of the unit hydrograph (X_4) respectively. In addition, the Nash-Sutcliffe coefficient's deviation value obtains 0.73, which is considered a good performance model (0.65<NSE<0.75). The percent bias (PBIAS) calculation obtains the deviation of 3.5 %, showing this GR4J model in Keser watersheds can be accepted (under 5%). Therefore, the coefficient of determination (R-squared) obtains 0.66, a good fit performance model for daily data and 0.951 for monthly data inferring that the model has a strong correlation performance.

Keywords: *Rainfall-runoff model, GR4J, Tugu dam, Nash-sutcliffe, TRMM*

1. INTRODUCTION

Hydrology analysis plays an essential role in water resources management, development, and design involving the transformation process in the rainfall-runoff model, flood routing, flood design, etc. In Indonesia, the major challenge of water structure design is the deficiency of hydrological data, which involves precipitation and discharge/runoff. The hydrological model is an alternative solution to estimate relevant results in the unobserved area by referring to the same watershed characteristics in the observed part. The current and future water resources management and development challenges vary greatly because of several issues of land-use changes, population growth, parameter socio-economic development, and the effect of climate change [1]. Therefore, sustainable water resource management has become crucial in achieving water security in Indonesia.

Evaluating the water supply and demand in a watershed as a part of the integrated water resources management, operation, and maintenance program in Indonesia contributes to the decision-making consideration and strategy of the government to realize sustainable management of water resources. The rainfall-runoff transformation models are widely applied to estimate a robust result when AWLR (Automatic Water Level Recording) has not been installed. GR4J (Génie Rural à 4 Parameters Journalier) is a daily rainfall-runoff model with four independent parameters to optimize the model: production tank capacity (X1), subterranean exchange coefficient (X2), route storage one-day capacity (X3), and unit hydrograph time base (X4) [2]. GR4J model has a strong foundation and efficient modeling, which developed from the previous GR3J [3][4] model.

From previous studies conducted by [2], the GR4J model result gives an excellent performance compared to several rainfall-runoff models such as Tank Models [5], IHACRES [6], SMAR [7], TOPMODEL [8], HBV [9], Xinanjiang model [10]. This model has been applied to various watersheds in Gambia [11], France [12], Slovenia [12], Australia [12], Cyprus [13], India [14], and Morocco [15].

Several studies related to rainfall-runoff modeling using GR4J have been conducted in Indonesia. [16] conducted the modeling of the upstream Citarum river basin using GR4J, and the result obtained a similar value of simulation discharge compared with observed discharge. [17] conducted analysis of ENSO impact on streamflow of Cisangkuy watershed of West Java using GR4J. Therefore, this study presents numerical modeling to simulate the rainfall-runoff model using GR4J of the Keser watershed. This is because there is a need to analyze more analysis and examine the performance of the GR4J model related to watershed characteristics in Indonesia.

2. RESEARCH SIGNIFICANCE

The study related to the GR4J model is not widely applied in Indonesia. Therefore, this study aims to test the model's performances associated with the characteristics of the Keser watershed in the Trenggalek district of East Java, Indonesia, which generally has a dendritic type of watershed. In addition, it estimates the reservoir inflow of the Tugu dam located downstream of the Keser watershed.

3. METHODOLOGY

3.1 Study Area

The Keser Watershed is located in Trenggalek District, the Southern part of East Java Province of Indonesia (Figure 1), with 43.06 km^2. In the Keser watershed, the Tugu dam has been built for the primary purposes of irrigation, hydropower, water supply, and flood control with the adequate storage of 9.3 million m^3. GR4J's daily rainfall-runoff aims to analyze the efficacy of the model of the Keser watershed to assist the government in the operation and management process, such as total flow downstream of its watershed or in the Tugu dam.

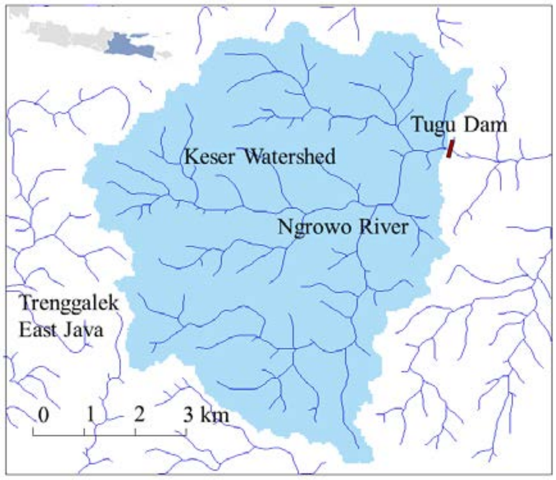

Fig. 1 Keser Watershed in Ngrowo River of Trenggalek-East Java

3.2 Hydrology Data

The rainfall and potential evapotranspiration are two significant inputs of the GR4J model. The data used was The TRMM (Tropical Rainfall Measuring Mission) near-real-time low-latency daily precipitation time series obtained from Giovanni NASA (National Aeronautics and Space Administration) [18] and JAXA (Japan Aerospace Exploration Agency) [19]. It was compared with observed discharge data collected from the hydrometry gauge station in the observed area. In addition, daily observer runoff data was available for at least two years during 2017-2018 (Figure 2).

The TRMM data can be used in Indonesia because the focus of TRMM is rain measurement in tropical areas [20]. The utilization of TRMM data in Indonesia, such as the clustering of precipitation patterns in Indonesia [21] and the forecast evaluation and accuracy distribution f TRMM daily rainfall in Makassar strait, South Sulawesi [22].

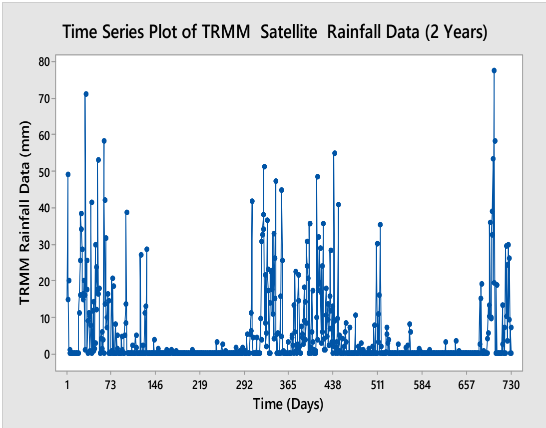

Fig. 2 TRMM rainfall satellite data

The potential evapotranspiration for the catchment was calculated using the Penman method (Equation 1). The parameter of meteorological data (wind velocity, solar radiation, air temperature, humidity, and water vapor pressure) were collected from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG).

$$ETo = C. [W. Rn + (1-W). f(U). (ea-ed)] \quad (1)$$

Where Eto is the reference crop evapotranspiration (mm/day). Rn signifies net radiation of evaporable water per day (mm/day). W defines as a parameter temperature-related weighting factor. The wind-related function is f(U). Ea is the difference in saturation vapor pressure at mean air temperature. The mean actual air vapor pressure (established before) in mbar is defined by Ed. Finally, C is the weather-adjustment factor that accounts for day and night situations.

3.3 GR4J Model

With two water stores (production and route) and four parameters to optimize during calibration, the GR4J model is one of the simplest rainfall-runoff lumped hydrological models [2]. Figure 3 depicts a GR4J schematic diagram model. The first two parameters are the water balance and the transfer functions. These parameters are calibrated using an optimization algorithm developed by [3][4], with the Nash [23] criterion used as an objective function.

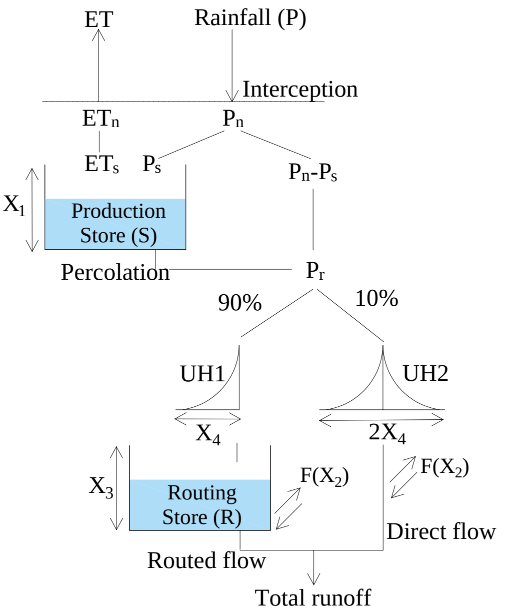

Fig. 3 The schematic diagram of the GR4J rainfall-runoff model [2].

GR4J model has four independent parameters to optimize the daily rainfall-runoff model, such as production tank capacity (X_1), underground exchange coefficient (X_2), the one-day capacity of the routing storage (X_3) and time base of the unit hydrograph (X_4). The first two inputs are daily rainfall (P) and evapotranspiration (E). Then, the model neutralizes P by E to obtain the net rainfall (Pn) and net evapotranspiration (En) [2], calculated in Equations 2 and 3.

If P > E, then
$$Pn = P - E \text{ and } En = 0 \quad (2)$$

If P < ET, then
$$Pn = 0 \text{ and } En = E - P \quad (3)$$

$$Ps = \frac{X1.\{1-(\frac{S}{X1})^2\}.\tanh(\frac{Pn}{X1})}{1+\frac{S}{X1}.\tanh(\frac{Pn}{X1})} \quad (4)$$

Where X1 (mm) specifies the maximum capacity of the production (SMA) store, S represents storage, and Pn denotes the model's net rainfall. When En is not zero, the actual evaporation rate is calculated as a function of the level in the production store to determine the quantity of Es (equation 5) that defines the evaporated water from the storage.

$$Es = \frac{S.\{2-\frac{S}{X1}\}.\tanh(\frac{En}{X1})}{1+(1-\frac{S}{X1}).\tanh(\frac{En}{X1})} \quad (5)$$

As a parameter/variable function of the reservoir content, a percolation leakage (Perc) from the production store (S) is determined.

$$\mathbf{Perc} = \mathbf{S}.\left\{\mathbf{1} - \left[\mathbf{1} + (\frac{\mathbf{4S}}{\mathbf{9X1}})^{\mathbf{4}}\right]^{-\mathbf{1/4}}\right\} \quad (6)$$

The reservoir content calculated in equation 7 to represent the total quantity of water in the route store (R) shows that the percolation (perc) value is steadily lower than S.

Equation 8 gives the total amount of water that reaches the routing functions (Pr).

$$S = S - Perc \quad \mathbf{(7)}$$

$$Pr = Pn - Ps + Perc \quad (8)$$

This percolation and Pn-Ps result from the total runoff (Pr), then divided into two parts. The unit hydrograph one (UH1) is routed ninety percent (90%) of its total runoff, and the remaining (10%) is routed by UH2, which is the length of UH2 twice UH1 (Equations 9 and 10).

$$Q1(i) = 0.1 \,.\, \sum_{k=1}^{m} HU2(k) * Pr(i - k + 1) * (1) \quad (9)$$

$$Q9(i) = 0.9 \,.\, \sum_{k=1}^{L} HU1(k) * Pr(i - k + 1) \quad (10)$$

The calculation of groundwater exchange (F) that affected both UH flow components (UH 1 and UH 2) is given in equation 11.

$$\mathbf{F} = \mathbf{X2}[\frac{\mathbf{R}}{\mathbf{X3}}]^{\mathbf{7/2}} \quad (11)$$

Where R is the routing store level affected by the underground exchange coefficient (X2) and capacity of the routing storage (X_3).

The routing store (R) level is updated by adding the output Q9 (UH_1) and F. Afterwards, the outflow discharge of the reservoir (Qr) is calculated using equation 12. Meanwhile, the total streamflow calculation of UH 2 and F becomes Qd (equation 13). The total discharge/streamflow is finally obtained by summing Qr and Qd (equation 14). The computation flowchart organization of GR4J is shown in Figure 4.

$$\mathbf{Qr} = \mathbf{R}.\left\{\mathbf{1} - \left[\mathbf{1} + (\frac{\mathbf{R}}{\mathbf{X3}})^{\mathbf{4}}\right]^{-\mathbf{1/4}}\right\} \quad (12)$$

$$Qd = \max(0; Q1 + F) \quad (13)$$

$$Q = Qr + Qd \quad (14)$$

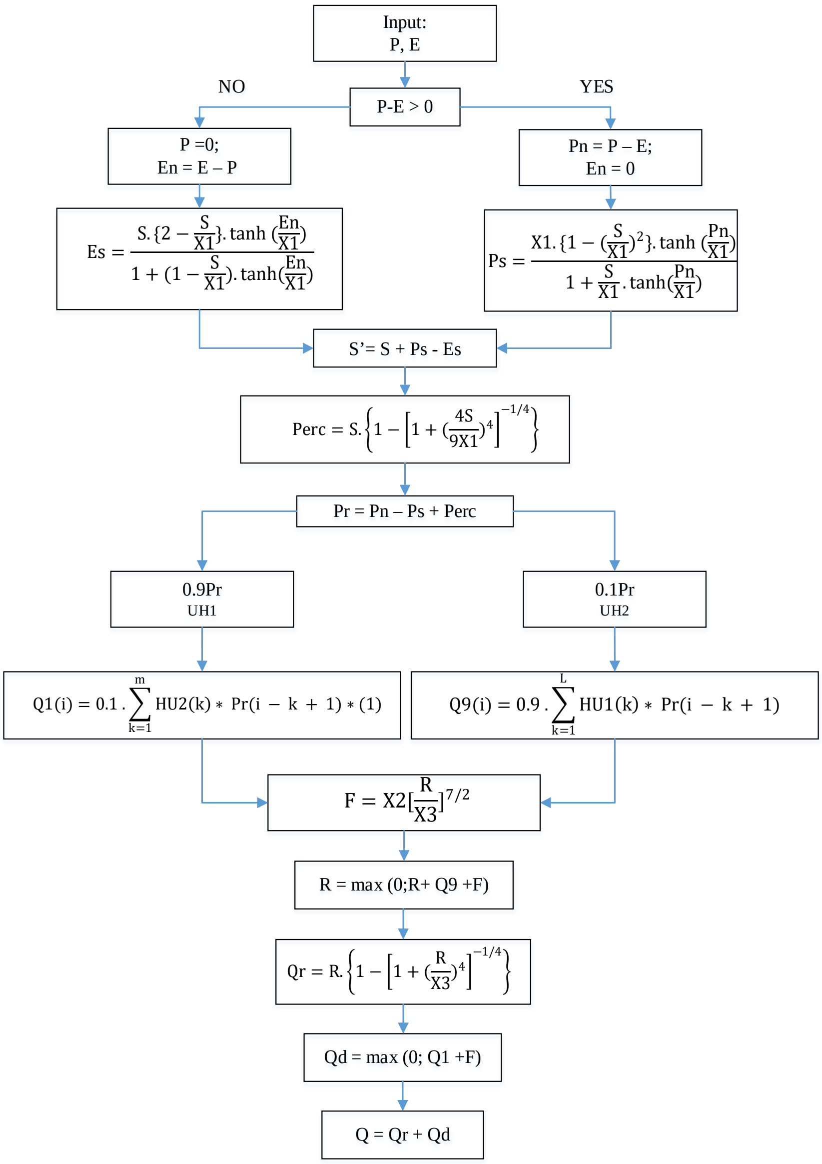

Fig. 4 Computation organization of GR4J

3.4 Model Evaluation

The Nash-Sutcliffe model efficiency coefficient (NSE), percent bias (PBIAS), linear correlation coefficient (R), and determination coefficient (R^2) will be used to evaluate the resilience GR4J model's performance and accuracy. The Nash–Sutcliffe model efficiency (NSE) (equation 15) evaluates the GR4J model's predictive value. The Nash–Sutcliffe model efficiency (NSE) is widely used in hydrology modeling for testing the fit goodness of the model. The Nash-Sutcliffe coefficient (NSE) value ranges between -∞ and 1 it could be applied to a variety of several model types. An NSE value of 1 indicates that the estimated discharge model is a perfect fit and consistent with the observed data. Meanwhile, a performance of 0 indicates that the model has the same prediction ability as the mean discharge of the observed data. The observed data mean is better than model predictions/simulations when the efficiency is less than zero (NSE<0) [23].

$$\mathbf{NSE} = \frac{\sum_{i=1}^{n}(Qoi - Qsi)^2}{\sum_{i=1}^{n}(Qoi - Qom)^2} \quad (15)$$

Qoi is the observed discharge, Qsi is the simulated discharge, and Qom is the mean observed discharge.

Percent Bias (PBIAS) measures the average trend of simulations above or below the data observations. PBIAS's best fit value is zero, and its low-level estimation value indicates the most accurate model simulation. The positive value of PBIAS implies an underestimating of discharge simulations, while the negative value indicates an overestimation of discharge simulations [24] calculated using the following equation:

$$\mathbf{PBIAS} = \frac{\sum_{i=1}^{n} Qoi - Qsi}{\sum_{i=1}^{n} Qoi} * \mathbf{100} \quad (16)$$

Pearson's correlation coefficient calculates linear correlation (R) to estimate the linear dependence /relationship of discharge simulations and observations (two sets of data). The linear correlation coefficient value ranges from -1 to 1 which the zero (0) value suggests no relationship, whilst minus one (-1) value indicates the inverse relationship [25].

$$\mathbf{R(Qo, Qs)} = \frac{cov\,(Qo,Qs)}{\sigma o.\sigma s} * \mathbf{100} \quad (17)$$

4. RESULT AND DISCUSSION

This GR4J model implements daily rainfall-runoff transformation of the Keser watershed with 2-year data available in the study area (2017-2018). The calibration data used to obtain the performance of the GR4J model was a 730 observation daily dataset (2-year). The performance was evaluated using three parameters, namely NSE, percent bias (PBIAS), and linear correlation coefficient (R). The calibration result of the Nash-Sutcliffe coefficient (NS) and linear correlation coefficient (R) should be close to one, and PBIAS should be close to zero.

The optimum result of the model was evaluated from the iteration process of all four parameters, which obtains the minimum deviation. The final result of the best performance of each parameter is shown in Table 1 below. The comparison result of daily GR4J simulation and observation discharge in the Keser watershed is shown in Figure 5. Thus, the result of the monthly GR4J simulation and observation discharge comparison is shown in Figure 6.

Table 1 The optimum result coefficient and deviation of model parameters.

Model Parameter	Coef.
X_1: Production tank capacity (mm)	7.85
X_2: Underground exchange coefficient (mm)	2.52
X_3: One-day capacity of the routing storage (mm)	3.93
X_4: time base of the unit hydrograph (days)	-1.35

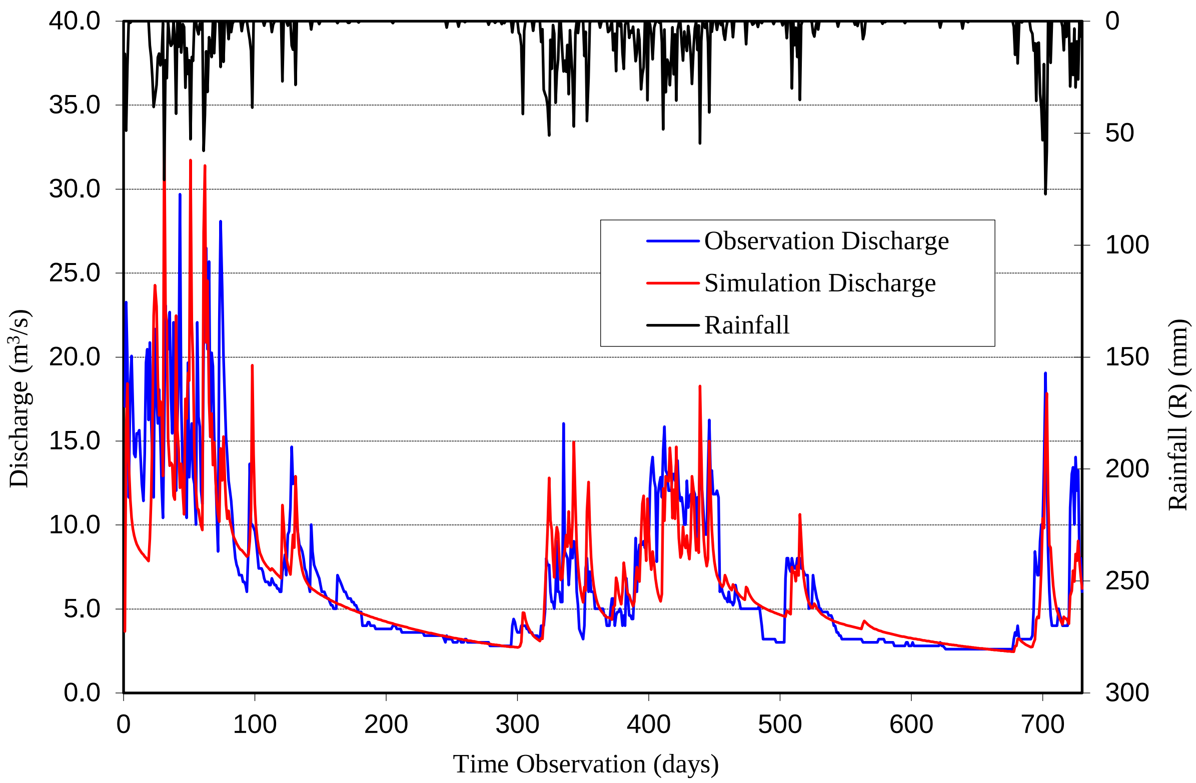

Fig. 5 The comparison result of GR4J simulation and observation discharge in Keser watershed (daily data)

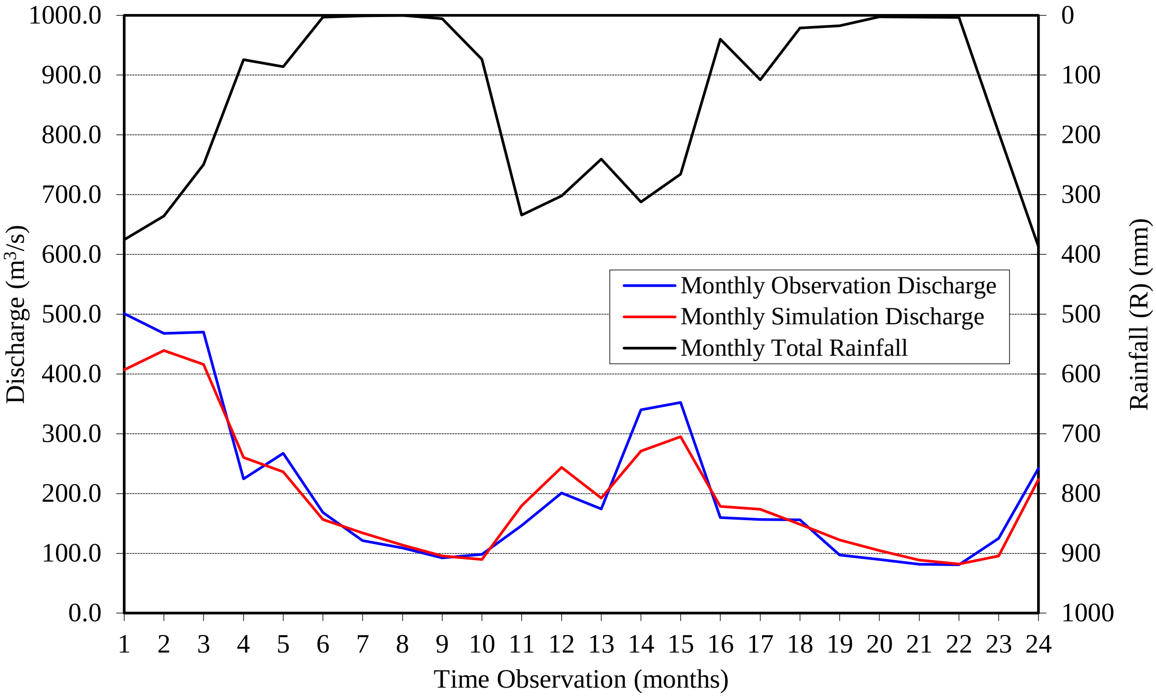

Fig. 6 The comparison result of monthly GR4J simulation and observation discharge in the Keser watershed

From Table 1, the best performances of the model for the coefficient result of production tank capacity (X_1) was 7.85, the underground exchange coefficient (X_2) was 2.52, the one-day capacity of the routing storage (X_3) was 3.93, and the time base of the unit hydrograph (X_4) was -1.35.

The deviation value using the Nash-Sutcliffe coefficient (NSE) obtained 0.73, which is considered a good performance model (0.65<NSE<0.75). Moreover, the percent bias (PBIAS) calculation with the deviation of 3.5 % shows this GR4J model in Keser Watersheds can be accepted (under 5%). Therefore, the 0.813 linear correlation coefficient (R) obtained with a 0.66 coefficient of determination (R^2) inferred that the model has good fit performance (Figure 7).

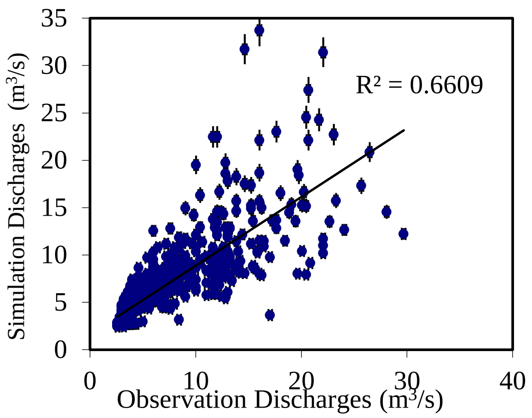

Fig. 7 The coefficient of determination (R-squared)) of the daily GR4J model in the Keser watershed

The coefficient of determination (R^2) result of monthly GR4J simulation and observation discharge obtained better results compared with daily data with 0.951 and inferred that the model has a strong correlation performance (Figure 8). The monthly simulation contributes to the decision-making consideration and managing strategy of the irrigation water supply as a part of the integrated water resources management in Indonesia.

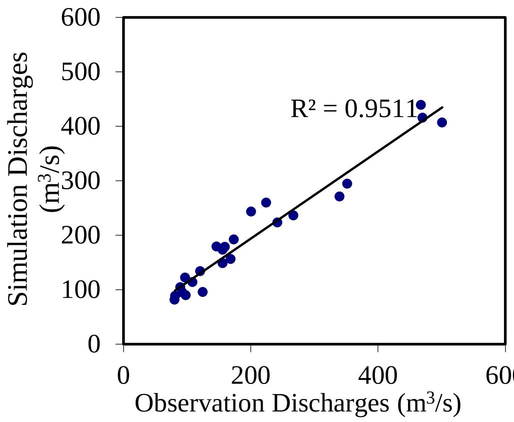

Fig. 8 The coefficient of determination (R-squared) of the monthly GR4J model in the Keser watershed

5. CONCLUSION

Analysis of GR4J model to estimate the prediction of Tugu dam inflow and provide a general description of water availability in Keser watershed obtained good performance. From the optimization parameters, the coefficient result of production tank capacity (X_1) was 7.85, the underground exchange coefficient (X_2) was 2.52, and the one-day capacity of the routing storage (X_3) was 3.93, and the time base of the unit hydrograph (X_4) was -1.35.

Using the Nash-Sutcliffe coefficient (NSE), the model's accuracy was 0.73, which is considered a good performance model. In addition, the deviation for the percent bias (PBIAS) calculation was 3.5 % (under 5%). Therefore, the 0.66 coefficient of determination (R squared) obtained indicates a good fit performance model. The coefficient of determination (R squared) result of monthly GR4J simulation and observation discharge obtained better results compared with daily data with 0.951 and inferred that the model has a strong correlation performance.

6. ACKNOWLEDGMENTS

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