

UDK/*UDC*: 004.9:556.166-047.48(594)
Izvirni znanstveni članek – *Original scientific paper*
DOI: 10.15292/acta.hydro.2023.05

Prejeto/*Received:* 17.08.2023
Sprejeto/*Accepted:* 30.01.2024
Objavljeno na spletu/*Published online:* 04.03.2024

COMPARISON OF FLOOD HYDROGRAPH PREDICTION BETWEEN SYNTHETIC UNIT HYDROGRAPH METHODS AND RAIN-ON-GRID MODEL FOR KATULAMPA WATERSHED, INDONESIA

PRIMERJAVA NAPOVEDI POPLAVNEGA HIDROGRAMA MED METODAMI SINTETIČNEGA HIDROGRAMA ENOTE IN MODELOM MREŽNIH PADAVIN ZA POVODJE KATULAMPA, INDONEZIJA

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Abstract

In this paper, 6 synthetic unit hydrograph (SUH) methods, namely Snyder, SCS, GAMA-1, ITB-1, ITB-2, and Nakayasu, were compared against a rain-on-grid model (HEC-RAS) for flood hydrograph prediction in the Katulampa watershed, Indonesia. HEC-RAS was used with an open-access, ~30 m resolution digital elevation model (DEM), i.e. the Advanced Land Observing Satellite (ALOS). The relative error of the hydrograph results (peak discharge and time-to-peak) were compared with the observed data, while the errors in the hydrograph's shape were detected using the Root Mean Square Error ($RMSE$) and Pearson Product Moment Correlation ($PPMC$). We found that HEC-RAS could predict the flood hydrograph significantly more accurately than the SUH methods, yielding the $RMSE$ value of 1.98 m^3/s and the $PPMC$ value of 0.93. This study remains an interesting example of how modern computational tool can improve the runoff prediction of conventional SUH methods.

Keywords: DEM, Katulampa, synthetic unit hydrograph, HEC-RAS, rain-on-grid.

Izvleček

V tem prispevku smo primerjali šest metod sintetičnih hidrogramov enote (SUH), tj. Snyder, SCS, GAMA-1, ITB-1, ITB-2 in Nakayasu, z modelom mrežnih padavin (HEC-RAS) za napoved poplavnega hidrograma v povodju Katulampa v Indoneziji. HEC-RAS je bil uporabljen z odprtodostopnim digitalnim modelom višine (DEM) z ločljivostjo ~30 m, tj. Advanced Land Observing Satellite (ALOS). Relativno napako rezultatov hidrograma (najvišji pretok in čas do vrha) smo primerjali z opazovanimi podatki, medtem ko smo napake v obliki hidrograma opazovali z uporabo korena povprečne kvadratne napake ($RMSE$) in Pearsonove korelacije

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produkta momentov ($PPMC$). Ugotovili smo, da lahko HEC-RAS napoveduje poplavni hidrogram bistveno natančneje kot metode SUH, saj poda vrednost RMSE 1,98 m^3/s in vrednost PPMC 0,93. Ta raziskava dobro ponazarja, kako lahko sodobno računalniško orodje izboljša napoved odtoka z uporabo običajnih metod SUH.

Ključne besede: DEM, Katulampa, sintetični hidrogram enote, HEC-RAS, mrežne padavine.

1. Introduction

Extreme flood events in the past decade have caused Indonesia to experience large amounts of damage both to citizens' lives and to the economy itself. Based on National Agency for Disaster Countermeasure (2018), flood became the most frequent disaster in 2017, causing 180 people to go dead/missing, 106 people to suffer injuries, and more than 2.5 million people to be evacuated in Indonesia. To anticipate more damage in the future, a well-integrated system for flood risk management is of importance; several aspects are required herein, of which 1 relates to flood hydrograph prediction.

The unit hydrograph (UH) method is probably the simplest approach for flood hydrograph prediction. This method was first presented by Sherman (1932) to develop a hydrograph for any given storm using a unit depth of effective rainfall or runoff. A UH for a basin can be derived in 2 ways: (1) directly using both measured discharge and rainfall data for a selected event or (2) only using rainfall data with a synthetic unit hydrograph (SUH) formula. Both methods can be used in flood hydrograph estimation for gauged basins with observed rainfall-runoff data; however, for the ungauged ones, only SUH formulas can be employed. Most of the SUH formulas were derived empirically, and thus, due to some uncertainties, predicting flood hydrographs in ungauged basins is quite challenging.

In Indonesia, SUH methods have been used in many projects to estimate flood hydrographs for ungauged basins. Several SUH methods, e.g. Snyder (Snyder, 1938), SCS (Soil Conservation Service) (Soil Conservation Service, 2002), GAMA-1 (Gadjah Mada – 1) (Harto, 1985), ITB-1 & ITB-2 (Institut Teknologi Bandung 1 and 2) (Natakusumah et al., 2011), and Nakayasu (Soemarto, 1987) have been documented as the Indonesian standard in the document (Badan Standarisasi Nasional, 2016). In fact, each SUH method was developed based on empirical formulas derived from several basin parameters, i.e. watershed area, length of main river, basin slope, etc., and even derived only from certain basin locations. Therefore, such SUH methods may not be universally applicable to discharge predictions, especially for ungauged basins.

Generally, every SUH method has 1 or more coefficients that must be determined by its users. In many cases, such coefficients do not have an initial value, thus requiring initial guesswork; even if there is a certain range for such coefficients, they must be calibrated based on basin characteristics and/or measured discharge data. In (Badan Standarisasi Nasional, 2016), 3 SUH methods, i.e. GAMA-1, SCS, and Snyder, were designated as the standard techniques and the other 3 SUH methods, i.e. Nakayasu, ITB-1, and ITB-2, were included as the optional ones to be used by engineers in Indonesia to estimate flood hydrographs for hydraulic projects. All of these methods are classified into the traditional SUH techniques, which all account for inconsistency and subjectivity for 2 main reasons (Singh et al., 2014). First, iterative procedures are required to fit the SUH parameters. Secondly, several adjustments are often needed to ensure that the area under the SUH curve corresponds to the unit rainfall excess.

Some works that used SUH methods for flood hydrograph prediction are mentioned here. The GAMA-1 method was used to estimate flood hydrographs for the Bangga watershed in Central Sulawesi, Indonesia (Andiese, 2012), and the results here were compared against the observed discharge, calculated statistically using the Log-Pearson III distribution. Significant errors of up to 20% were noted between the GAMA-1 results and the observed data. The Nakayasu method was employed to compute flood hydrographs for 7 small-scale basins in Turkey, indicating that the error ratios between the calculated and observed data were significant, and, thus, the original Nakayasu method was modified using a regression analysis with the observed average unit hydrograph data (Aydin and Bagatur, 2017). The modified method was able to calculate peak discharge and time-to-peak with less significant errors. Nevertheless, it was stated that the modified formulas can only be applied to hydrograph predictions for similar basin characteristics.

The Snyder and SCS methods were compared to estimate runoff hydrograph in 8 watersheds in Nigeria, showing that the differences for the peak values obtained with both methods varied from 13.14% to 63.30% (Salami et al., 2017). It was concluded that the SCS method was recommended due to its additional morphometric parameters, i.e. its watershed slope. However, this result requires further investigation as no observed data were included. A recent study by Kristianto et al. (2019) compared the results of several SUH methods, namely Snyder, Nakayasu, GAMA-1, and ITB-1, against the measured discharge for the Tukad Pakerisan watershed in Bali, Indonesia. It was observed that the Snyder, Nakayasu, GAMA-1, and ITB-1 methods produced average errors of 20%, 25%, 57%, and 35% respectively for peak discharge prediction, and it was suggested that the coefficients be modified for the Snyder method. Further, Kristianto et al. (2019) found that such a modification would also be useful in analyzing other basins, but only those with similar characteristics.

All the above phenomena show the flaws inherent to SUH methods, and thus, they are not always reliable for flood hydrograph prediction. This problem relates to adjusting or modifying the empirical parameters of such SUH methods, especially for GAMA-1 and Nakayasu, thus making the process quite complex. Note that even if adjusting the parameters is possible to achieve accurate predictions, such adjusted values are not readily applicable even to other similar cases. Therefore, it is of importance to find another approach for flood hydrograph computation. This can be achieved, one of which, by means of rain-on-grid (shallow water) modeling.

With rain-on-grid modeling, simulations for hydrologic (overland) flow processes are simultaneously integrated with hydrodynamic (channel) flow. This is achieved by incorporating rainfall minus infiltration as a source term into the mass conservation part of the shallow water equations, so that flow depth for each computational grid can be computed. Thereafter, the depth value is employed together with bed roughness in the momentum conservation part of the shallow water equations to calculate velocities. Some previous works that had successfully utilized rain-on-grid modeling are mentioned here.

Hall (2015) conducted rain-on-grid simulations using MIKE-21 for watersheds in Rockingham, Australia covering 7 km^2 and 176 km^2 of basin areas. The model could accurately predict the peak hydrograph for both watersheds with only insignificant discrepancies observed for the recession limb. Ginting and Mundani (2019) used NUFSAW2D for rainfall-runoff simulations on complex topography in Glasgow, UK. The results showed the rain-on-grid model could properly compute the hydrograph by accounting for the bed topography values of the watershed area as a direct factor to influence the overland flow characteristics, which is not the case with SUH methods. In Godara et al. (2023), TELEMAC-2D was employed to predict the flood hydrograph for the Sleddalen catchment in Møre and Romsdal, Norway. Results were produced in accordance to the observed data especially for the peak and time-to-peak values; however, discrepancies were still noted for the recession limb albeit insignificant.

Recently, the capability of HEC-RAS was tested by David and Schmalz (2020) for the Fischbach catchment in Germany. Their rain-on-grid simulation results were sufficiently accurate and shown beneficial to provide a more comprehensive and accurate description of the floodplains and the source of overland flow in the catchment area compared to the simulations with traditional SUH methods. In Zeiger and Hubbart (2021), HEC-RAS was used to simulate the flood hydrograph of the Hinkson Creek watershed in the USA. It was stated that rain-on-grid modeling with HEC-RAS is considered accurate when several aspects are satisfied, i.e. using areal effective precipitation, calibrating the parameters (the bed roughness and infiltration values), ensuring no backwatering sources outside of the computational domain and during saturated antecedent soil moisture conditions, and using DEM data that can properly describe the overland flow paths. In Hariri et al. (2022), an advanced domain decomposition technique was applied to rain-on-grid simulations with HEC-RAS to calculate the flood hydrograph of the Saar watershed in France (1,747 km²) with quite accurate results. Their technique allowed HEC-RAS to be employed for a watershed with an area of 1,747 km^2 discretized using 2.8 million computational meshes, so the bed topography values can be directly considered for hydrograph computations. All these previous studies have shown that rain-on-grid modeling is a promising approach for flood hydrograph predictions in real-world scenarios.

In this study, 6 SUH methods (Snyder, SCS, GAMA-1, ITB-1, ITB-2, and Nakayasu) were compared against a shallow water model (HEC-RAS 6.1) to compute flood hydrographs for the Katulampa watershed in Indonesia, which is categorized as a midscale catchment. One of the required inputs for HEC-RAS simulation is a topographic map. Fine-resolution topographic data, e.g. the type derived from light detection and ranging (LiDAR) techniques, are fundamental for conducting proper rain-on-grid simulations. However, such data are expensive and may not be available for data-sparse regions. Hence, open-access digital elevation models (DEMs) can be used instead.

Within the past decade, DEMs with different types/sources and resolutions were used for hydrologic/hydraulic simulations. Saksena and Merwade (2015) demonstrated that Shuttle Radar Topography Mission (SRTM) (~30 m) was accurate for simulations of river flood depth. Jarihani et al. (2015) found that SRTM (~30 m) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (~30 m) were accurate for flood inundation simulations. Munoth and Goyal (2019) compared different resolutions of SRTM (i.e. ~30 m, ~90 m, and ~180 m) and found that the 90-m resolution yielded among the most accurate results for hydrologic simulations. Azizian and Brocca (2020) stated that ALOS (~30 m) was better than SRTM (~30 m) and ASTER (~30 m) for flood water level predictions. Muthusamy et al. (2021) discovered that SRTM (~30 m) was appropriate for flood inundation. Tesema (2021) found that ALOS (~30 m) was better than SRTM (~30 m) for peak flood analysis. Chymyrov (2021) showed that ALOS (~30 m) provided higher vertical accuracies and was better than SRTM (~30 m) for hydrologic analysis.

The previous works above indicate that no single DEM type/source is universally applicable for producing more accurate results in hydrology/hydraulic simulations. It can also be noted that changing the resolution of a DEM by resampling or coarsening it from its original/finer resolution may lead to different outcomes. Also, using finer-resolution DEMs does not necessarily yield more accurate results than using the coarser ones, indicating that DEM resolution is not the only key factor in rain-on-grid modeling but also the DEM type/source itself is important. In our study, ALOS (~30 m) – a satellite-derived DEM that can be downloaded at no cost – was used. This study will pose a new opportunity for computing flood hydrographs more accurately within a framework of rain-on-grid modeling (instead of using conventional SUH techniques), thus helping related stakeholders enrich and standardize modeling techniques and related procedures for ungauged basins, especially in data-sparse regions such as Indonesia.

2. Case Study

The case study investigated in this research is the Katulampa watershed, with the outlet point coordinates of 06°38'00.6" S and 106°50'13.7" E. We selected this case study as it is located in a data-sparse region, which is a common phenomenon in Indonesia. The stream network generation and the watershed delineation were carried out using a QGIS (Quantum Geographic Information System) tool, as shown in Figure 1. The stream network was generated using the flow direction and flow accumulation techniques based on DEM data. Once the stream network is created, the watershed can be delineated.

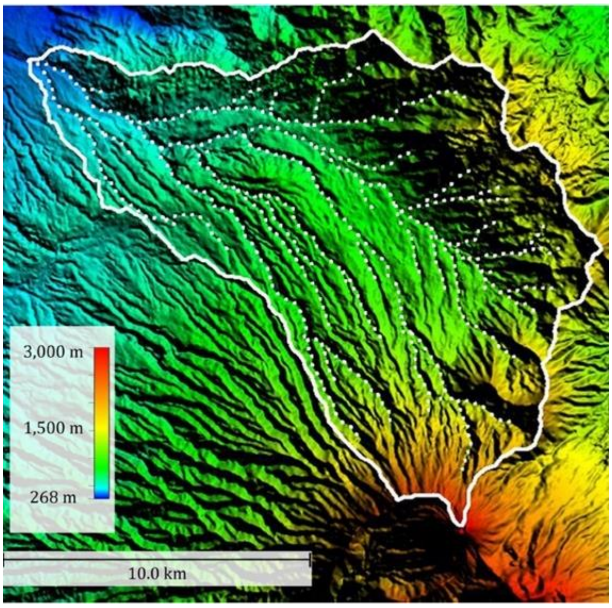
Note that the basin in Figure 1 was created using ALOS (the details will be explained in the next section). The basin characteristics, i.e. watershed area (A), length of main river (L), length toward the weight point of the area (L_c), and river slope (S), are shown in Table 1.

The land use map of the Katulampa watershed was obtained from the local authority, see Figure 2. There are 3 land use types covering the Katulampa watershed, i.e. forest, agriculture, and urban area. The upstream part of the watershed is dominated by forests, while most of the downstream part is dominated by urban areas. The rainfall data for our analysis were based on 3 ground stations, located inside the watershed, namely Citeko, Gunung Mas, and Gadog, while the automatic water level recorder (AWLR) station was located at the Katulampa station, see Figure 3. The rainfall data were obtained from the local authority and available with hourly distribution.

Preglednica 1: *Značilnosti povodja Katulampa*

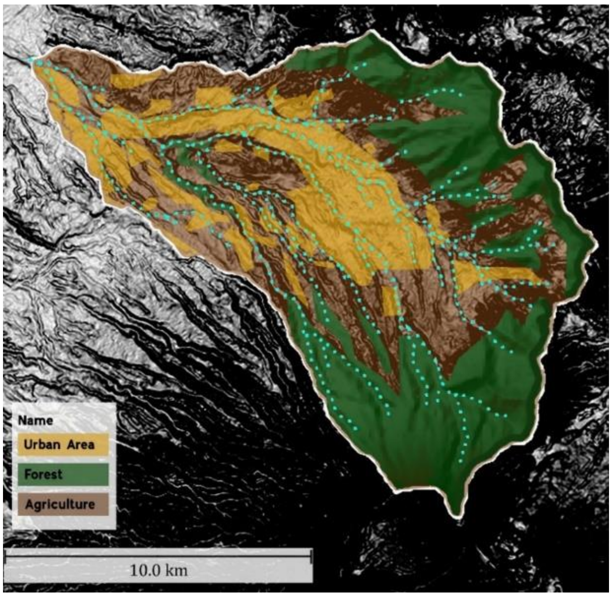
Table 1: *Characteristics of the Katulampa watershed*

A (km^2)	L (km)	L_c (km)	S (%)
151.34	23.41	9.53	6.05



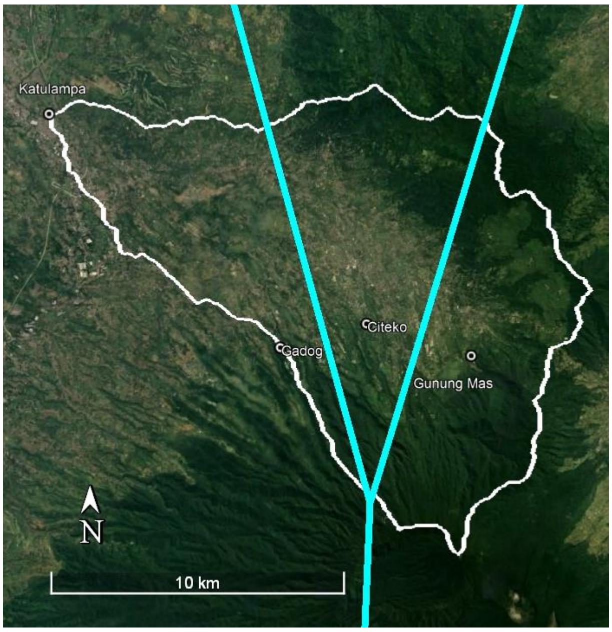
Slika 1: *Rečna mreža in razvodnica z uporabo ALOS.*

Figure 1: *Stream network and watershed using ALOS.*



Slika 2: *Karta rabe tal povodja Katulampa.*

Figure 2: *Land use map of the Katulampa watershed.*



Slika 3: *Lokacija postaj in Thiessenovi poligoni.*

Figure 3: *Location of the ground stations and the Thiessen polygon.*

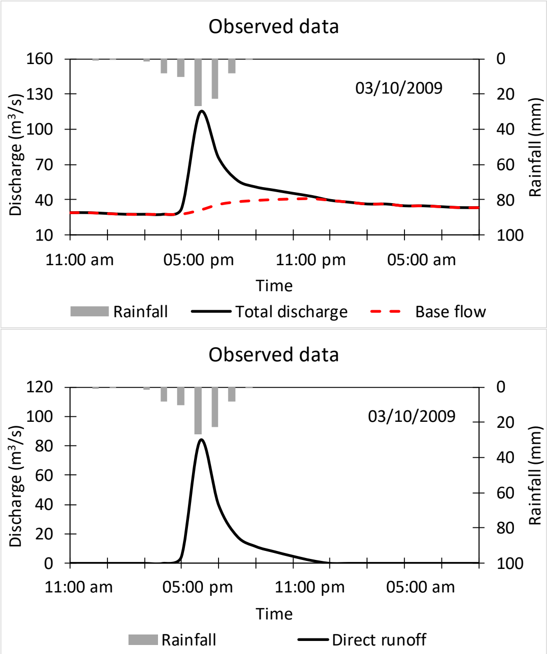
Fundamentally, using more ground station data inside the watershed will be a better way to represent the rainfall distribution and characteristics spatially. However, we could not find any other rainfall data except from the 3 aforementioned stations. Alternatively, satellite-derived rainfall data such as TRMM (Tropical Rainfall Measuring

Mission) or GPM (Global Precipitation Measurement) may be employed. Nevertheless, such satellite-derived data require proper corrections before using them for computations because they are affected by a lot of uncertainty, such as sun radiation, temperature, cloud cover, etc. (Senjaya et al., 2020). In our study, the regional rainfall values for the Katulampa watershed were computed using the Thiessen polygon method, as seen in Figure 3.

The flood event recorded on 10 March 2009 was selected as our case study. In fact, sample data were recorded by the local authority during 2009. Notwithstanding, we chose this flood event because it was one of the periods for which we had a complete dataset. Meanwhile, other periods included some missing rainfall or discharge values. In addition, this event was selected since the flood occurred after the dry season, thus representing an initially dry bed condition for rain-on-grid simulations. The observed discharge obtained from the local authority is shown in Figure 4, which indicates a total value of the direct runoff and baseflow.

Since the focus of our study was on comparing the direct runoff between the observed data, SUH methods, and HEC-RAS, the baseflow therefore had to be separated from the total discharge. This was conducted by the local authority using a standard digital filtering approach for baseflow separation suggested by Lyne and Hollick (1979). Using this approach, it can be noted that the peak direct runoff value is approximately 83.40 m^3/s. The direct runoff data in Figure 4 is then used for the analysis in this paper.

An important parameter that should be known for hydrograph computation is the Antecedent Moisture Condition (AMC), being an indicator of the relative wetness or dryness of a watershed that provides soil moisture storage before a storm event. The AMC relates to a soil infiltration rate, to determine the effective rainfall required either for SUH or HEC-RAS calculations. However, there was no observation conducted for soil samples in the Katulampa watershed, making it difficult to determine the AMC for the selected flood event. According to the local authority, approximately 5 to 7 days before 10 March 2009, no rainy day was observed. Following this information as well as the fact that 2009 was the dry season in Indonesia, the AMC is assumed to be relatively dry.



***Slika 4:** Opazovani pretok pred (zgoraj) in po (spodaj) izločanju baznega odtoka. Histogram padavin je pridobljen s Thiessenovo metodo.*

***Figure 4:** Observed discharge before (top) and after (bottom) baseflow separation. The rainfall histogram was obtained using the Thiessen method.*

3. Materials and Method

Six SUH formulas (Snyder, SCS, GAMA-1, ITB-1, ITB-2, and Nakayasu) were tested to compute flood hydrograph for the Katulampa watershed and then compared against the observed data and HEC-RAS. For the sake of simplicity, only single-basin analysis was applied to each SUH method. Note that the detailed SUH formulas are not described here; hence, interested readers are referred to Ponce, 1994, for the Snyder and SCS methods, Harto, 1985, for the GAMA-1 method, Natakusumah et al., 2011, for the ITB-1 and ITB-2 methods, and Soemarto, 1987, and Aydin and Bagatur, 2017, for the Nakayasu method.

HEC-RAS version 6.1 is a free-license software that can be used for general applications of open-channel flow modeling. Hence, it can also be applied to rain-on-grid simulations by modeling the related physical process from precipitation and infiltration to overland flow. The fully dynamic solver in HEC-RAS was selected to solve the 2D shallow water equations. This solver employs the sub-grid bathymetry approach proposed by Casulli (2009), which allows for using coarse computational grid by incorporating fine topographic features into computations. Note that the details of the numerical solutions used in HEC-RAS are not discussed here but are available in the HEC-RAS Manual (U.S. Army Corps of Engineers, 2016).

DEM is used as the input data for HEC-RAS simulation. Several types of DEM, i.e. LiDAR or satellite-derived data from coarse to fine resolutions are possible for HEC-RAS. In this work, ALOS is used. ALOS or *Daichi* comes from the name of a Japanese satellite launched in 2006. ALOS has 3 Earth observation sensors, i.e. the Panchromatic Remote-sensing instrument for Stereo Mapping (PRISM) for digital elevation mapping, the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) for precise land coverage observation, and the Phased Array type L-Band Synthetic Aperture Radar (PALSAR) for day-and-night and all-weather land observations. ALOS has a horizontal resolution of ~30 m and a vertical accuracy of (less than) 5 m. ALOS can be downloaded at no cost (ALOS, 2006).

Besides DEM, other data such as the Manning coefficient and infiltration rate are required in HEC-RAS. The infiltration value is also required for defining the effective rainfall for the convolution computation of SUH methods. As no field measurement of soil samples was available, both the Manning coefficient and infiltration values were estimated using empirical formulas based on land use data.

In this regard, we follow the range for the Manning coefficient according to Bhola et al. (2019), which found agriculture to be the only data category that was very sensitive to the Manning value. This finding was supported by simulations with 1,000 combinations (and finally reduced to 143 combinations) of the Manning coefficient consisting of agriculture, forest, urban area, and water body. For the infiltration rate, we follow the range suggested by Mireille et al. (2019), see Table 2. The calibrated values in Table 2 will be explained later in the next section. Note that curve number (CN) values are also presented in Table 2 based on each land use type as these values are used in SUH methods to compute lag time. To determine CN values, hydrologic soil group data are required, which are defined according to the harmonized world soil database (HWSD) map (Fischer et al., 2008).

Preglednica 2: *Manningov koeficient in stopnja infiltracije.*

Table 2: *Manning coefficient and infiltration rate.*

Land Use Type	Manning coefficient ($s/m^{1/3}$)		Infiltration rate (mm/hour)	
	Range based on (Bhola et al., 2019)	**Calibrated values (for HEC-RAS)**	**Range based on** (Mireille et al., 2019)	**Calibrated values (for HEC-RAS)**
Forest	0.110–0.200	0.160	30.0-156.0	90.0
Agriculture	0.025–0.110 (*reduced to 0.032–0.047*)	0.045	3.0-30.0	30.0
Urban area	0.040–0.080	0.060	0.0-10.0	5.0
Land Use Type	**Curve number (CN)**			
	Hydrologic Soil Group (HSG)	**Used values (for SUH methods)**		
Forest	C	70		
Agriculture	C	88		
Urban area	C	94		

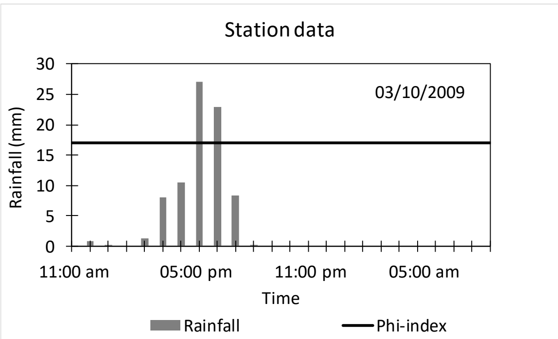
For SUH methods, the hydrograph convolution between the effective rainfall and the computed results was conducted to obtain direct runoff values. Equation (1) is the hydrograph convolution formula written as:

$$Q_n = \sum_{i=1}^{n} P_i U_{n-i+1} = P_n U_1 + P_{n-1} U_2 + \cdots + P_1 U_n \quad (1),$$

where n is the time, P_i is the rainfall excess at time increment i, and U_n is the hydrograph ordinate at time increment i. The infiltration model available in HEC-RAS was adopted, namely the Deficit and Constant method, which employs a hypothetical single soil layer to calculate the changes in moisture content.

4. Results and Discussion

Because no soil sample was taken in the Katulampa watershed to test the infiltration characteristics, the phi-index method was consequently used to estimate the infiltration value for the SUH methods. The value was calibrated iteratively to minimize the Root Mean Square Error ($RMSE$) between the observed and computed discharges for each SUH method. After the calibration, the most appropriate phi-index value using the Snyder, SCS, GAMA-1, ITB-1, ITB-2, and Nakayasu methods averaged 17 mm/day; see Figure 5. Note that the phi-index value of 17 mm/day may be interpreted as an average infiltration rate of forest, agriculture, and urban area from the range given in Table 2; it fits the average of the lowest range values for forest, agriculture, and urban area (30, 3, and 0 mm/hour, respectively).

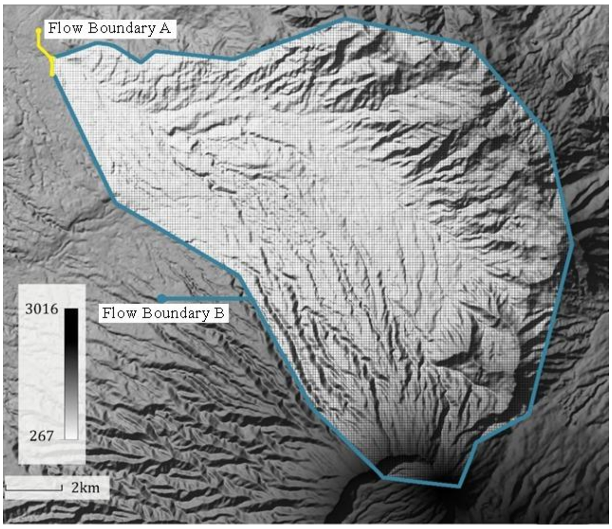


***Slika 5:** Vrednost indeksa Phi za efektivno količino padavin.*

***Figure 5:** Phi-index value for effective rainfall.*

For HEC-RAS modeling, 3 parameters must be set, namely computational domain, boundary condition, and initial condition. Several components are required to define computational domain, i.e. DEM, domain boundary, mesh size, Manning coefficient, and infiltration rate. Unlike SUH computations, rain-on-grid modeling can be done without any specific watershed boundary; for example, a computational domain can be set with a rectangular shape following a general DEM file format. The shallow water model then directly transforms rainfall to overland flow so that water flowing to a certain point (inside the computational domain) can be automatically exported as a flow hydrograph.

In this study, the domain boundary in HEC-RAS was determined in such a way where the outermost boundary of the computational domain was set outside the boundary of the watershed previously shown in Figure 1. Note that we could have even simply set the computational domain with ALOS to be rectangular; however, we did not do so, as we wanted to reduce the domain size and thus save computational time. The outermost boundary of the domain (Flow Boundary B in Figure 6) was specified as flow boundary (with the normal depth condition in HEC-RAS). Flow Boundary A in Figure 6 indicates a boundary line, on which the flow hydrograph results were extracted.



***Slika 6:** Nastavitev računalniške domene za HEC-RAS.*

***Figure 6:** Computational domain setup for HEC-RAS.*

The regional rainfall computed with the Thiessen method was applied uniformly to the computational domain in HEC-RAS as the boundary condition. To ensure that the direct runoff value was yielded for the simulation – so it could be fairly compared with the results of SUH methods – it was assumed that all areas of the computational domain in Figure 6 were initially dry. This follows the assumption of the relatively dry AMC that was previously explained.

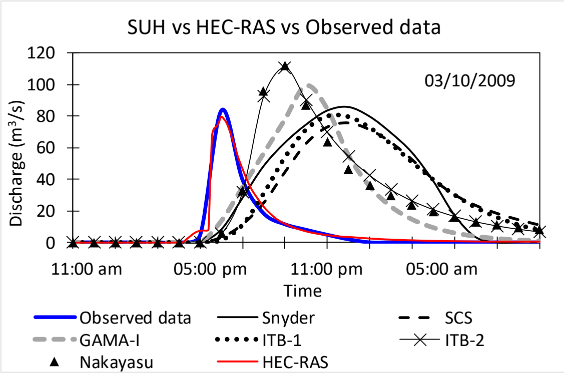
For rain-on-grid simulations, computational meshes with a size of 30 m were used. Note that we observed no significant effects on the numerical results when using a grid size finer than the DEM resolution, see also (Ginting et al., 2021) for a similar investigation regarding the computational mesh size and DEM resolution for dam-break modeling. The computation interval was set to 1 second (fixed time step) with a total simulation time of 24 hours. The interval of hydrograph output was specified to be 5 minutes. All default parameters were applied such as 0.003 m of water depth tolerance and finite difference matrix solver with skyline/Gaussian approach.

Still, the other 2 inputs for HEC-RAS, namely the Manning coefficient and infiltration rate, had to be determined. Finding suitable values for both data sets is very challenging because inferring their effects on streamflow is not straightforward if both the Manning coefficient and infiltration values are simultaneously modified. It becomes more complex since no measurement of soil sample was available for this project. To simplify the calibration procedure, first we follow (Bhola et al., 2019) to consider that only agriculture is sensitive to the Manning value. The same assumption was also applied to the infiltration rate. The $RMSE$ values between the computed and observed data were used for the calibration.

The first stage for the calibration was to set average values for Manning coefficient (0.04 s/m$^{1/3}$) and infiltration (17 mm/hour) values constantly for agriculture, while both values for forests and urban areas were gradually altered, aiming to know the sensitivity of forest and urban area to the Manning coefficient and infiltration values. Using the minimum, median, and maximum numbers for each range of the Manning coefficient and infiltration values produces a total of 81 combinations. At this stage, we observed that using different Manning coefficient and infiltration values for both forests and urban areas only resulted in insignificantly different $RMSE$ values, and thus they are insensitive to the Manning coefficient and infiltration values.

The next stage was to set constant Manning coefficient and infiltration values for forests and urban areas, and then to gradually alter the values for agriculture. For this, the median values were used for forests and urban areas. Meanwhile, the Manning and infiltration values for agriculture were gradually altered with an interval of 0.005 s/m$^{1/3}$ and 3 mm/hour, respectively. This gives 198 combinations. Having observed the results with the lowest $RMSE$ value, the calibrated Manning coefficient and infiltration values for all land use data can be obtained, see Table 2. Note that because the horizontal spatial resolution of ALOS (~30 m) is coarser than the actual river width that ranges from 10 – 20 m (from upstream to downstream), a sub-grid channel approach was not implemented in our work, and therefore it was not possible to attribute a specific Manning value to the main channels/rivers.

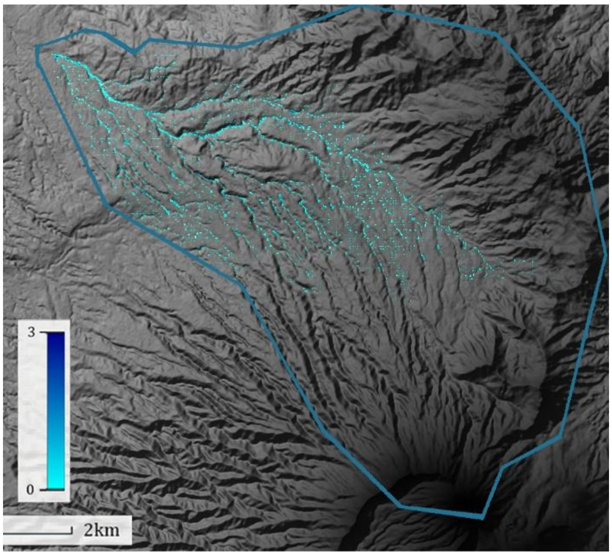
Figure 7 shows a comparison of the direct runoff between the results of the convoluted SUH methods, the HEC-RAS model, and observed data. One can observe that GAMA-1 overpredicted the peak discharge and could not capture the rising limb accurately. Both Nakayasu and ITB-2 showed almost identical results, by overpredicting the peak discharge. Also, both methods could not appropriately compute the recession limb. The Snyder method could predict the peak discharge appropriately, but it did not correctly compute the time-to-peak and time base. Both SCS and ITB-1 showed identical results, which slightly underestimated the peak discharge approximately until 5 hours. Also, they were inaccurate in predicting both rising and recession limbs.



Slika 7: *Primerjava neposrednega odtoka med rezultati SUH, modelom HEC-RAS in opazovanimi podatki.*

Figure 7: *Comparison of direct runoff between the convoluted SUH results, HEC-RAS model, and observed data.*

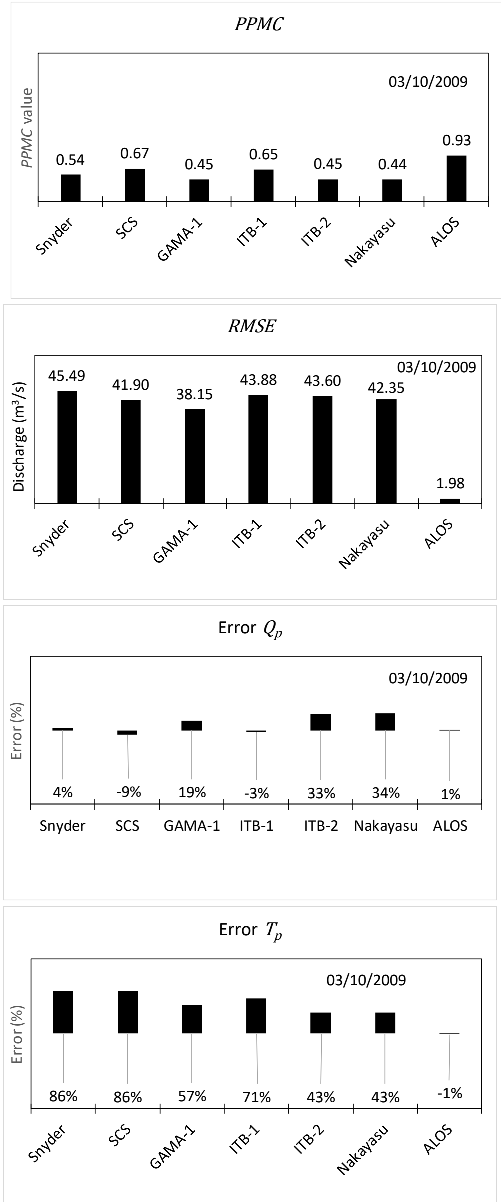
In contrast, ALOS was able to capture the peak discharge as well as the rising and recession limbs appropriately. In Figure 8, the spatial distribution of the maximum water depth for the direct runoff during the simulation time with HEC-RAS is presented. This visualization was made with a threshold of 1 cm for the depth. Note that the threshold value applies only to the visualization but not to the computation. In other words, the minimum runoff depth considered for HEC-RAS computations depends on the machine precision used.



Slika 8: *Rezultati HEC-RAS: največja globina vode v času simulacije.*

Figure 8: *HEC-RAS results: maximum water depth during the simulation time.*

We understand that although the hydrograph results at the outlet can be reproduced well by rain-on-grid modeling, the surface water distribution over the catchment in reality might not be properly represented. Unless a (high-resolution) satellite image is used to observe the distribution of surface water during the flood event or unless spatially distributed, measured data are available, it would be difficult to validate the surface water distribution shown in Figure 8. Unfortunately, the local authority could not provide any satellite images for this case study. Also, we were not able to find any open-access earth observation (EO) databases with proper spatial resolutions for our case study. For instance, we checked 2 open-access EO databases, namely GloFAS-ERA5 and ERA5-Land, with resolutions of ~5 km and ~11 km, respectively. Both databases obviously cannot represent the distribution of surface water over the Katulampa watershed properly due to very coarse resolution.



Slika 9: *Primerjava napak* $\boldsymbol{Q}$ *in* $\boldsymbol{T_P}$, $\boldsymbol{RMSE}$ *in* $\boldsymbol{PPMC}$.

Figure 9: *Comparison of the errors of* $\boldsymbol{Q}$ *and* $\boldsymbol{T_P}$, $\boldsymbol{RMSE}$, *and* $\boldsymbol{PPMC}$.

In order to evaluate the accuracy of the SUH methods and HEC-RAS model, we compared the results for 3 parameters: peak discharge (Q), time-to-peak (T_P), and hydrograph shape. For the first 2 parameters, the errors were computed using a percentage of relative error, while the last one was assessed using $RMSE$ and Pearson Product Moment Correlation ($PPMC$). Note that a relative error may result in a negative sign indicating a smaller computed value than the observed data. A $PPMC$ value expresses how well the calculated results and the observed data are related. Four groups of correlation are normally assigned to the $PPMC$ value: (a) greater than ±0.5 for strong positive/negative, (b) ±0.3 – ±0.5 for moderate positive/negative, (c) 0 – ±0.3 for weak positive/negative, and (d) 0 for no correlation.

Figure 9 shows the error comparison between the SUH, HEC-RAS, and observed data. All the SUH methods produced the $RMSE$ values above 38 m^3/s, thus indicating significant inaccuracy of the results. Nevertheless, some SUH methods, i.e. Snyder and ITB-1, could still capture the peak discharge with errors of 4% and -3%, respectively, but again all the SUH methods failed to compute the time-to-peak by yielding errors above 40%. The $PPMC$ values indicate that Snyder, SCS, and ITB-1 are the SUH methods that show strong, positive correlations with the observed data, whereas GAMA-1, ITB-2, and Nakayasu can only exhibit a moderate, positive correlation with the observed data.

It can be noted that HEC-RAS gave the best $PPMC$ value (0.93), indicating inter alia a (very) strong, positive correlation with the observed data. For hydrograph shape prediction, HEC-RAS was again able to be accurate with a $RMSE$ value of 1.98 m^3/s, thus yielding the most appropriate data among the SUH methods. HEC-RAS also outperformed the others in calculating the peak discharge and time-to-peak by producing significantly lower errors of 1% and -1%, respectively.

In our opinion, the fundamental reason why SUH methods produced inaccurate results is because such methods assume that all portions of net rainfall are transformed into runoff, which thereafter flows entirely to the specified outlet as a hydrograph. In addition, SUH methods (with a single-basin approach) only utilize average basin characteristics – e.g. basin area, basin slope, basin length, length toward the weight point of the basin, and basin slope – derived from DEM data. Note that even if a semi-distributed (multiple-basin) approach is applied, each sub-basin will still employ average basin characteristics. Consequently, physical rainfall-runoff (overland flow) processes may be inaccurately represented by SUH methods.

In general, none of the SUH methods is consistent in yielding accurate results either for hydrograph shape, peak discharge, or time-to-peak prediction. Snyder, SCS, and ITB-1 produce comparable results for the 3 parameters, as do ITB-2 and Nakayasu. Meanwhile, GAMA-1 shows different results from the others. The differences from each method are due to the different formulas of time-to-peak, time base, and lag time. Such formulas are derived based on the basin-length parameter alone, except for GAMA-1, which considers other parameters besides basin length, such as the order of river and basin shape factor.

In contrast, with rain-on-grid modeling, overland flow processes are taken into account based on bed contour values assigned to each DEM grid. Although its accuracy is influenced by DEM resolution and DEM source/type, rain-on-grid modeling does not use average basin characteristics. Therefore, it can compute flood hydrograph more properly than SUH methods. Unlike the previous works of Shustikova et al. (2019), Costabile et al. (2020), David and Schmalz (2020), Zeiger and Hubbart (2021), and Hariri et al. (2022), which employed HEC-RAS with fine-resolution DEMs (~1 m), our findings indicate that rain-on-grid modeling using a satellite-derived DEM (ALOS) with a coarser-resolution of ~30 m can predict the flood hydrograph accurately. This can be achieved with the calibrated Manning coefficient and infiltration values.

5. Conclusion

A comparison has been presented of flood hydrograph computation among 6 SUH methods (Snyder, SCS, GAMA-1, ITB-1, ITB-2, and Nakayasu) and the HEC-RAS model, with rain-on-grid numerical modeling using ALOS. As a case study, a historical flood event in the Katulampa watershed was selected for direct runoff comparison.

To assess the accuracy of the computed results, 3 indicators were used: the relative error, root mean square error ($RMSE$), and Pearson Product Moment

Correlation ($PPMC$). None of the SUH methods was consistent in giving accurate predictions for the hydrograph shape, peak discharge, and time-to-peak. In contrast, rain-on-grid modeling with HEC-RAS using ALOS was proven to be consistent in accurately predicting the hydrograph shape, peak discharge, and time-to-peak. A very strong, positive correlation with the observed data indicated by a $PPMC$ value of 0.93 for the rising and recession limb phases was also shown by HEC-RAS.

In this study, we have presented that, although the SUH methods are simple, useful, and straightforward for flood hydrograph prediction in ungauged basins, they are not always reliable. Meanwhile, rain-on-grid modeling with the calibrated Manning coefficient and the infiltration value may result in accurate results of flood hydrographs. Indeed, extending rain-on-grid modeling to ungauged basins is not straightforward, as calibration for both Manning coefficient and infiltration must be conducted. Therefore, we suggest comprehensively investigating the sensitivity of the Manning coefficient and infiltration values by considering more land use data in the future.

Finally, we conclude that rain-on-grid modeling is a promising approach for flood hydrograph computation and expect that it may be considered as an alternative to conventional SUH methods in predicting flood hydrographs in (ungauged) basins, especially in data-sparse regions such as Indonesia. While finer-resolution, satellite-derived DEMs do not necessarily provide more accurate results than the coarser ones, and thus can sometimes be more reliable for rain-on-grid modeling, the availability of measured DEMs with (very) fine resolution, i.e. LiDAR data (~1 m), can be quite useful to enable a sub-grid channel approach. In this regard, specific Manning values can be attributed to the main channels/rivers, and hence, the physical processes of both overland and channel flows can be simultaneously simulated in rain-on-grid modeling.

Acknowledgment

Bobby Minola Ginting, as the principal investigator (PI), acknowledges the Institute for Research and Community Service (Lembaga Penelitian dan Pengabdian kepada Masyarakat) of Parahyangan Catholic University for supporting this work with a funding number III/LPPM/2023-02/35-P. The partial funding by Ikatan Alumni Teknik Sipil (IATS) of Parahyangan Catholic University (006/IATS-UNPAR/V/2020), for which Bobby Minola Ginting is the PI, is also gratefully acknowledged. The fruitful discussions with Theo Senjaya and Steven Reinaldo Rusli are also highly appreciated.

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