

HEC-HMS Based Hydrological Modeling for Assessing Reservoir Impacts on Flood Hydrographs in the Pacal Watershed

Yuliani Wahyu Sardana ^{1✉}

(1) Department of Civil Engineering, Bojonegoro University, Bojonegoro, Indonesia

Abstract: The Pacal Watershed in Bojonegoro Regency faces severe periodic flooding driven by intense tropical rainfall and land-use change, making the modeling of how the integration of the Pacal and Gongseng reservoirs attenuates flood hydrographs in small tropical catchments a critical issue. This study introduces a novel framework modeling hydrograph transformations resulting from the interaction between the historical Pacal Reservoir and the modern Gongseng Reservoir using HEC-HMS employing the SCS Curve Number loss method and Nakayasu SUH transformation achieving high predictive reliability with a Nash-Sutcliffe Efficiency score of $NSE = 0,81$. Simulation results demonstrate that dual-reservoir integration significantly mitigates downstream flood risks across 100-year to 1,000-year return periods, achieving peak discharge reductions of 55,46% to 59,38% ($320,9 \text{ m}^3/\text{s}$ to $379,6 \text{ m}^3/\text{s}$) and delaying peak arrival times by 2 to 6 hours with Pacal Reservoir attenuating $163,1 \text{ m}^3/\text{s}$ – $195,3 \text{ m}^3/\text{s}$ and Gongseng Reservoir reducing $107,2 \text{ m}^3/\text{s}$ – $115,6 \text{ m}^3/\text{s}$. This study proves that the reservoirs function as reliable hydraulic shock absorbers that extend the emergency evacuation lead-time window for vulnerable downstream communities. Furthermore, it reveals a storage efficiency decay phenomenon during extreme storm events due to finite surcharge storage capacity, underscoring the necessity of pre-release operational rule curves despite modeling limitations that omit sedimentation, baseflow, and channel routing.

Article history:

Received: 07 July 2026

Revised: 22 July 2026

Accepted: 24 July 2026

Published: 25 July 2026

Keyword:

Reservoir, Flood Hydrograph,
HEC-HMS

This is an open-access article under the [CC-BY-SA License](#).



How to cite: Sardana, Y. W. (2026). HEC-HMS Based Hydrological Modeling for Assessing Reservoir Impacts on Flood Hydrographs in the Pacal Watershed. RESWARA: Jurnal Riset Ilmu Teknik, 4(3), 561–576. <https://doi.org/10.70716/reswara.v4i3.725>

INTRODUCTION

Floods rank highest among the most destructive natural disasters worldwide, both in terms of their increasing frequency and the scale of devastation they inflict on human lives, ecosystem stability, and the resilience of global economic assets (Erena & Worku, 2018; Pabi et al., 2021). Hydrologically, a flood is defined as the inundation of an area that is normally dry, occurring when the rainfall volume exceeds the soil's natural infiltration capacity, daily evaporation rates, and the carrying capacity of the available drainage systems (Cirella et al., 2019). Along with the intensification of global climate change, hydrometeorological patterns have undergone extreme shifts, making high-intensity rainfall over short or prolonged durations more frequent (Buda et al., 2024). When these atmospheric phenomena interact with degraded landscapes, the aggressive transformation of rainfall into runoff takes place, triggering a surge in water discharge that exceeds the carrying capacity of natural river channels (Saltalippi et al., 2022). The massive losses incurred demand flood risk management strategies rooted in a comprehensive understanding of river hydrological behavior (Aggarwal et al., 2025).

Engineering interventions in water disaster risk management are categorized into non-structural and structural approaches. While non-structural tactics continue to develop, structural mitigation remains highly reliable, particularly in protecting rural and sub-urban areas that exhibit high spatial

vulnerability due to limited adaptive space (Prastica et al., 2021). One of the most vital structural instruments in flood control engineering is the construction of reservoirs (Ferdian et al., 2020), which serve as artificial storage systems that intercept, store, and control the energy and volume of runoff before it is released downstream at a safe capacity (Kalra et al., 2023).

Flood hydrograph analysis serves as an essential deterministic tool for evaluating the effectiveness of such water infrastructure. The hydrograph represents river discharge fluctuations as a function of time, serving as the primary key in flood forecasting, determining design flood discharge for hydraulic structures, and estimating inundation for mitigation purposes (Maulana & Sutopo, 2020). The construction of a reservoir can radically alter the geometric configuration of the flood hydrograph by influencing hydrograph attenuation, operating through three main pillars: effective storage capacity, gate operation management strategies, and spatial positioning along the river channel (Sukerte, 2022). When a flood wave enters a reservoir, the storage space acts as a shock absorber (Souza et al., 2017). Floodwater is temporarily stored, ensuring that the peak discharge exiting through the spillway is substantially smaller than the peak inflow, thereby reducing the amplitude of the hydrograph and minimizing downstream overflow risks (Wibowo et al., 2024). Furthermore, reservoirs modify the time axis by delaying the time required for the hydrograph to reach its peak downstream (lag time), which extends the evacuation window for downstream communities (Wang et al., 2023).

While the theoretical capacity of reservoirs to flatten sharp, flashy hydrographs into controlled release profiles is well-documented (Bartos & Kerkez, 2019), this mitigation capability is highly dynamic and context-dependent. Recent hydrological studies indicate that the initial storage level at the onset of rainfall plays a critical role; if the reservoir water level is already high due to previous rainfall events, the remaining flood storage becomes minimal, dropping the efficiency of peak discharge attenuation drastically an occurrence common during severe flood events or large return periods (Evangelista et al., 2025).

The varying characteristics of reservoir influence have been successfully demonstrated in large-scale system case studies, such as the collective reservoir networks along the Huai River Basin in China (Wan et al., 2018). However, existing research heavily focuses on single-reservoir impacts or massive, heavily managed cascading networks in sub-tropical zones. There remains a profound research gap in evaluating smaller-scale, localized multi-reservoir systems in tropical regions, where rapid soil saturation (Subrata & Putuhena, 2012) and severe climate-induced degradation intercept the structural performance of the dams.

Translating these dynamics to a regional locus, periodic flooding is a critical issue that continually plagues the Pacal Watershed in Bojonegoro Regency, East Java Province (Mulyanti et al., 2020). Topographically situated in a downstream low-lying basin, Bojonegoro's vulnerability is compounded by massive upstream environmental degradation driven by land-use changes (Harjono & Widhiastuti, 2019). The conversion of forest areas into agricultural lands and settlements has reduced the surface roughness coefficient and water retention capacity, causing rainwater to transform directly into high-velocity surface runoff (Nada & Sunariya, 2025). Consequently, the natural hydrograph of the Pacal Watershed has become highly flashy, carrying high sediment loads that trigger severe river siltation and embankment erosion.

To address this, the government has implemented structural interventions, starting from the colonial-era Pacal Reservoir built in 1933 to the newly completed Gongseng Reservoir in 2021. Although this dual-reservoir infrastructure physically coexists within a unified hydrological system, a

critical knowledge gap persists. The concrete combined impact and operational interaction scheme between the historic Pacal Reservoir (which suffers from severe capacity-reducing sedimentation) and the modern Gongseng Reservoir have never been scientifically quantified or verified. No comprehensive hydrological model has yet mapped how these two distinct structural assets work in tandem to mitigate peak discharge components and shift the time-to-peak axis under various extreme rainfall return periods.

To address these critical gaps, this study aims to develop a comprehensive hydrological model using the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) to evaluate the effectiveness and operational dynamics of the dual-reservoir system in the Pacal Watershed. Specifically, this research models the flood hydrograph transformation to quantify the precise percentage of peak discharge attenuation and map the time-to-peak shift under multiple extreme rainfall design scenarios, including the 100-year, 500-year, and 1,000-year return periods.

The primary novelty of this study lies in the formulation of an integrated HEC-HMS framework that evaluates the joint performance of an aged, highly sedimented reservoir (Pacal) operating in tandem with a modern, fully functional reservoir (Gongseng) within a highly vulnerable tropical watershed. Unlike previous generic modeling studies, this research explicitly accounts for the modern constraints of capacity degradation in legacy infrastructure paired with new structural assets. The study provides new empirical insights into how dual-reservoir interactions alter hydrograph geometry during multi-century extreme weather events, offering an essential scientific foundation for optimizing flood control command chains and spatial disaster mitigation in downstream basins.

RESEARCH METHOD

Overview of the Research Location

The location used in this study is the Pacal Watershed of Bojonegoro Regency with a watershed area of 303.24 km² with a relatively flat topography where most of the area is in the lowlands. Land use in the Pacal Watershed of Bojonegoro Regency consists of agriculture, scrub forest, plantation, village, river, reservoir, industrial, land with scrub and land without scrub. Based on FAO, the type of soil in the Pacal watershed consists of 3 types of soil, namely dystic fluvisols, lithosols, and pellic vertisols, while based on the HSGS classification, it can be grouped into 2 types of soil, namely B and D. Figure 1 is the location of the study conducted in this study.

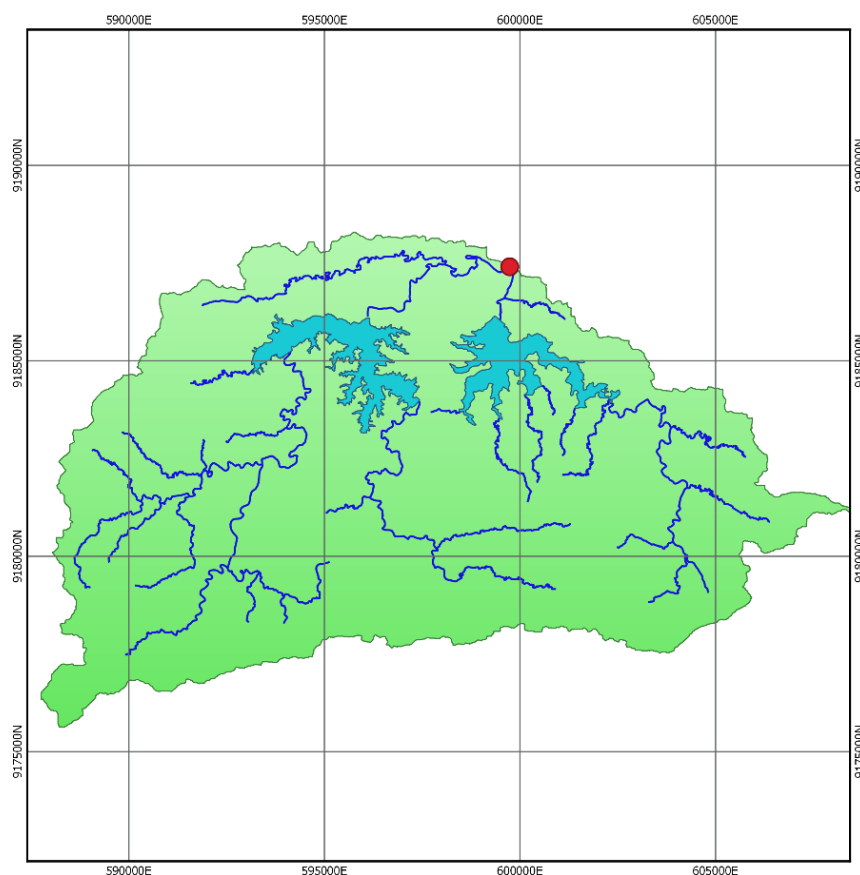


Figure. 1 Pacal Watershed Research Location

Data Collection and Preprocessing

This study utilized a combination of high-resolution spatial data and long-term hydrometeorological datasets obtained from several authoritative government agencies and institutional databases. Spatial delineation of the watershed, slope estimation, and channel routing were performed using the Digital Elevation Model (DEM) sourced from the DEMNAS portal (Badan Informasi Geospasial / BIG). Daily rainfall data spanning a 20-year observation period from 2002 to 2021 were obtained from the UPT PSDA Bojonegoro Regency, captured across seven strategically distributed gauging stations, namely Balen, Kapas, Jatiblimbing, Klepek, Tretes, Sukun, and Sugihan stations. To characterize the physical surface properties of the catchment, Land Use and Land Cover (LULC) maps were acquired from the Dinas PU Bina Marga Bojonegoro Regency, while regional soil classification maps were retrieved from the 2007 FAO-UNESCO global database. Furthermore, technical engineering parameters, including elevation-storage-discharge curves, spillway dimensions were provided by the BBWS Bengawan Solo.

To ensure the reliability and mathematical validity of the subsequent hydrological simulations, a rigorous data quality assessment and control protocol was strictly executed. The geospatial layers (DEM, LULC, and FAO Soil Map) were uniformized and re-projected into the Universal Transverse Mercator (UTM) Zone 49S coordinate system under the WGS 84 datum, allowing the absolute elimination of spatial displacement errors during watershed segmentation. Concurrently, the 20-year

historical hydrometeorological time-series data were subjected to an inconsistency and missing-value screening process. Minor data gaps of fewer than five consecutive days were statistically imputed using the Normal Ratio Method by leveraging adjacent station data to maintain data continuity across all stations.

Prior to direct integration into the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), the validated datasets underwent extensive preprocessing routines. The spatial datasets were analyzed within a GIS environment using the HEC-HMS extension; the DEM terrain model was initially subjected to a Fill Sinks algorithm to eliminate artificial pits, followed by the generation of flow direction and flow accumulation grids for the establishment of the physical boundaries, sub-basins, and drainage networks of the Pacal Watershed. The construction of a hydrological soil-vegetation matrix and the generation of the final spatial Curve Number (CN) grid were achieved through an advanced geospatial layering and vector intersection process executed within QGIS software. This layer integration combined the LULC vector datasets with the FAO Hydrological Soil Group (HSG) classifications (Groups A, B, C, and D) to systematically represent the soil moisture retention and surface runoff potential across the watershed.

Data Processing and Analysis

Plan Rainfall Analysis

The rainfall analysis of the plan begins by testing the consistency and absence of trends in the rain data using the RAPS method and the Spearman Method. Consistent and independent rain data will be used for regional rain calculations using the Polygon Thiessen Method using the help of QGIS software. The maximum daily rain of the resulting area will then be analyzed for a suitable distribution according to the match test, namely the Chi-Square test and the Smirov-Kolmogorov test so that the best distribution is obtained for the determination of rainfall for the re-current plan.

Hour-Time Rain Distribution

The rain distribution method used to convert daily rain data into rainy hours is ABM (alternating block method). Soliman's research states that the hyetograph of the ABM method is recommended for use for flood hazard assessment and stormwater drainage system applications (Soliman, 2022). The Modified Mononobe method is used to convert daily rain intensity into hourly rain intensity. The approach of the duration of rain is carried out using the time of concentration. The concentration time formula (t_c) used in this study is the Australian Rainfall Runoff (ARR) formula, the ARR formula is very dependent on the watershed area. The Modified Mononobe formula and the ARR formula are presented in Equation (1) and Equation (2).

$$i_T^t = \frac{RT_{24}}{T_c} \left(\frac{T_c}{t} \right)^{\frac{3}{2}}$$

where,

i_T^t : Rain intensity at duration to t with T year period (mm/rain),

RT_{24} : Maximum daily rain at the re-period of the year to be calculated (mm)

T_c : Concentration time (hours)

t : Duration of rain (hours)

$$T_c = 0,76 \times A^{0,36}$$

where,

T_c : Concentration time (hours)

A : Watershed Area (km²)

Synthetic Unit Hydrograph (HSS)

The estimation of design flood hydrographs in ungauged catchments or watersheds with deficient historical discharge records necessitates the deployment of Synthetic Unit Hydrograph (SUH) formulations due to the mathematical preclusion of direct hydrograph measurement techniques (Indarto, 2018). Selection of the Nakayasu SUH method in this study is based on its established adaptability and structural suitability in modeling the geomorphological characteristics of tropical and mountainous catchments within the Indonesian region (Rahmadani et al., 2024). The mathematical framework of the Nakayasu model correlates the geometric parameters of the watershed specifically stream length and sub-basin area with the temporal distribution of surface runoff without the requirement of extensive multi-decade calibration datasets. The peak discharge formula for Nakayasu HSS is as in Equation (3).

$$Q_p = \frac{1}{6} \left(\frac{A \cdot R_e}{0.3T_p + T_{0.3}} \right)$$

where,

Q_p : Peak discharge at flood conditions,

R_e : Effective rainfall period (1 mm),

A : Watershed area to be reviewed (km²),

T_{0.3} : Time of peak flooding – 0.3 times of peak discharge (hours),

T_p : Time from flood surface to hydrograph peak (hours)

Adoption of the Nakayasu model over alternative SUH methods is justified by its parameterization of the recession limb of the hydrograph (Buana et al., 2022). The Nakayasu method isolates the hydrograph drawdown curve into distinct exponential decay phases controlled by the T_{0.3} parameter, avoiding the mathematical instability or high sensitivity to regional coefficients often associated with the Snyder or Gama I methods under shifting geographical conditions (Ginting et al., 2023). This structural formulation ensures simulation stability regarding the detention storage behavior of reservoirs and catchments, establishing compatibility with the reservoir routing modules in HEC-HMS during the simulation of multi-century return periods (Sarkar & Drissia, 2024)

HEC-HMS Flood Hydrograph Model Simulation

The execution of the flood hydrograph simulations within the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) environment required a systematic parameterization of the physical and operational characteristics of the Pacal Watershed. To provide a clear overview of the configuration framework, the essential model parameters integrated into the HEC-HMS components are compiled in Table 1.

Table 1. HEC-HMS Model Component Parameterization

HEC-HMS Element	Hydrological Method/Process	Parameter/Input Requirement	Data Source/Derivation Method
Sub-basin	Loss: SCS Curve Number	Composite Curve Number (CN) Impervious Area (%)	QGIS spatial layering of LULC and FAO Hydrological Soil Groups
	Transform: Nakayasu SUH	User-Specified Unit Hydrograph coordinates	Empirical calculation of Nakayasu peak discharge (Q_p) and time lags
	Baseflow: None	Omitted	Direct surface runoff isolation approach
Reach	Routing: None	Omitted (Direct translation)	Focus placed on reservoir-driven attenuation mechanics
Reservoir	Routing: Outflow Structures	Elevation-Storage Curve Spillway Dimensions & Crest Elevation Discharge Coefficient (C_d)	BBWS Bengawan Solo technical specifications and as-built engineering drawings
Meteorological Model	Precipitation Input	Design Hyetographs (100, 500, 1000-year return periods)	Alternating Block Method (ABM) hourly distribution data
Control Specifications	Time Control	Simulation Start/End Time	Historical flood duration matching and structural response limits

The systematic breakdown of the model development, from raw data preparation to hydrograph output analysis, is illustrated in the following workflow diagram in Picture 2. The procedure for transforming rainfall into runoff within this structural model prioritized the isolation of surface runoff dynamics and reservoir routing. The geometric configuration of the basin model was established using a high-resolution DEM to build the topological connectivity between sub-basins, reaches, junctions, reservoirs, and the final sink (Msaddek et al., 2020).

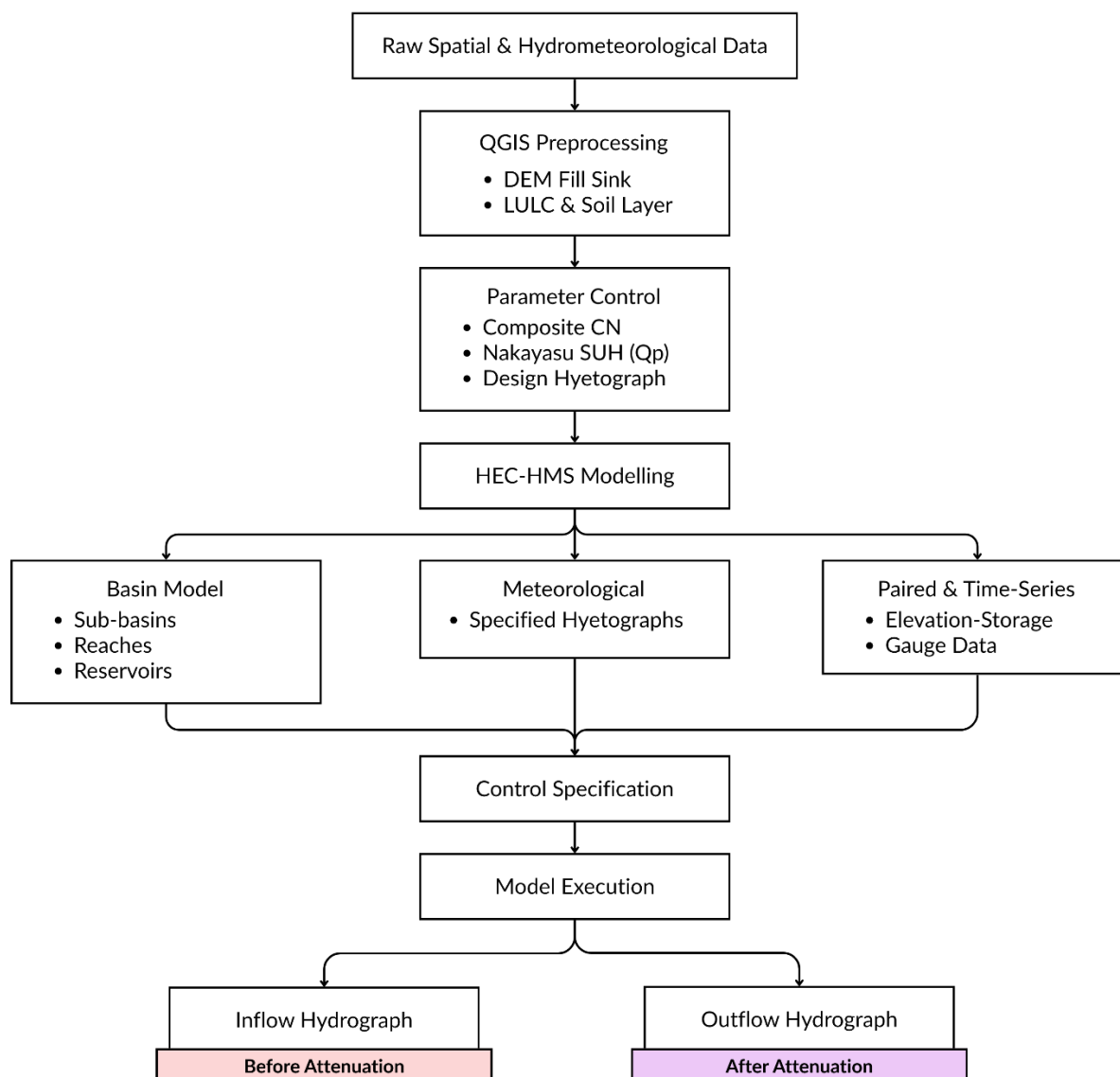


Figure 2. HEC-HMS hydrological model development workflow

The excess rainfall volume was calculated via the SCS Curve Number loss method, while its mathematical transformation into a direct runoff hydrograph was driven by Nakayasu SUH parameters and initial abstraction (Ia) calibrated in HEC-HMS and manually entered into the User-Specified Unit Hydrograph table. Baseflow and channel routing methods were deliberately omitted to prevent numerical masking of reservoir routing performance, with model accuracy validated using the Nash-Sutcliffe Efficiency (NSE) indicator. Finally, the dynamic interaction between the historical Pacal Reservoir and the modern Gongseng Reservoir was evaluated by routing simulated inflow hydrographs through paired data lookup tables (Elevation-Storage-Discharge relationships), strictly synchronized by HEC-HMS control specifications to map downstream flood peak attenuation and time-to-peak shifts across multi-century design storm events (Hamdan et al., 2021).

RESULTS AND DISCUSSION

Plan Rainfall Analysis

The calculation of the previous regional rain was carried out using the Polygon Thiessen Method using 7 rain stations that affected the study site. Rainfall analysis of the plan using the Log Pearson Type III method because according to the Chi-Square test, the best distribution results were obtained with a chi-criticism value of 9,488 greater than the chi-square of 3,400. The same result was also proven according to the Smirnov-Kolmogorov test obtained the best distribution results using the Log-Pearson III distribution with a Critical Delta value of 0,34 and a Maximum Delta value of 0,1003. The period used is a 100, 500 and 1000-return periods. The results of the precipitation analysis of the plan are presented in Table 2.

Table 2. Pacal Watershed Rainfall Plan

Period (Year)	R24 (mm)
100	98,924
500	103,474
1000	112,474

Hour-Time Rain Distribution

The process of inputting rain data in HEC-HMS software requires rain hours, so the average rain of the maximum daily watershed with a daily rain needs to be distributed into rain hours. The duration of the draft rain was calculated using the Australian Rainfall Runoff (ARR) method which gave a result of 7 hours. The results of the calculation of the design rain distribution using the ABM method are shown in Table 3.

Table 3. Rain Distribution Plan for the Pacal Watershed Hours

Hour	Hour-Time Rain Distribution (mm)		
	P100	P500	P1000
1	5.04	5.26	5.73
2	6.44	6.72	7.33
3	9.58	10.00	10.90
4	52.56	54.86	59.76
5	13.66	14.26	15.53
6	7.63	7.96	8.67
7	5.63	5.88	6.40

Synthetic Unit Hydrograph (HSS)

The transforming of rain into flow in this study used a synthetic unit hydrograph (HSS). In this study, the HSS used was HSS Nakayasu. The use of this HSS is based on the unavailability of river water level data from AWLR equipment at the point of review. The HSS will be inputted in the HEC-HMS hydrological modelling according to the area that has been generated. Table 4 contains the hydrograph parameters of the Nakayasu synthetic unit and Figure 3 shows the hydrograph of the Nakayasu synthetic unit to all Sub-watersheds.

Table 4. Hydrograph Parameters of Nakayasu Synthetic Unit Pacal Watershed

Parameters	Unit	Pacal Watershed			
		Sub DAS 1	Sub DAS 2	Sub DAS 3	Sub DAS 4
Watershed Area (A)	km ²	74,289	66,644	13,778	3,069
River Length (L)	km	18,166	20,000	11,772	3,605
Peak Discharge (Qp)	m ² /s	5,819	5,159	1,706	0,772
Peak Time (Tp)	Hours	2,326	2,496	1,888	0,824
Recession Time 0.3 (T0.3)	Hours	2,849	2,840	1,677	0,857
Concentration Time (tg)	Hours	1,454	1,560	1,180	0,515
Unit of Time (Tr)	Hours	1,090	1,170	0,885	0,386

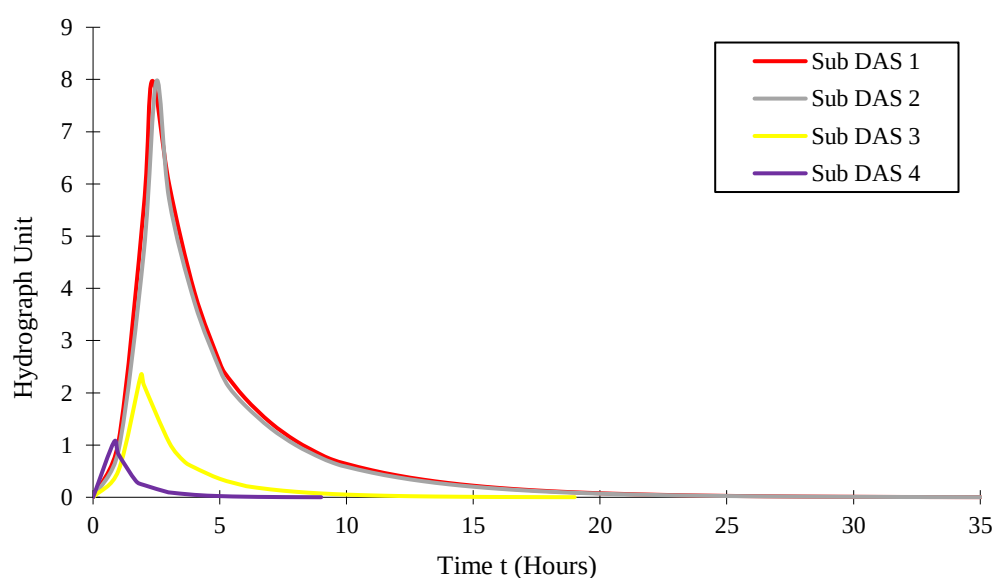


Figure 3. HSS Nakayasu Pacal Watershed

To verify predictive reliability, the HEC-HMS model performance was validated using the Nash-Sutcliffe Efficiency (NSE) indicator. The evaluation yielded a high performance score of $NSE = 0,81$, significantly exceeding the standard threshold benchmark of $0,65$. This strong goodness-of-fit statistic confirms an excellent agreement between the Nakayasu SUH parameterization and regional hydrological responses, thereby establishing a robust baseline for reservoir routing simulations.

HEC-HMS Flood Hydrograph Model Simulation

The simulation results reviewed from the outlet obtained peak discharge results on the flood hydrograph 100 years before the existence of the reservoir obtained by $540,4 \text{ m}^3/\text{s}$ at the 6th hour while after the existence of the peak discharge reservoir on the flood hydrograph produced $258,2 \text{ m}^3/\text{s}$ at the 9th hour. At the time of the 500 years, the peak discharge on the hydrograph before the existence of the reservoir was obtained at $585,4 \text{ m}^3/\text{s}$ in the 6th hour while after the existence of the reservoir, the peak discharge became $285,6 \text{ m}^3/\text{s}$ in the 9th hour. For 1000 years, the peak discharge was $684,5 \text{ m}^3/\text{s}$ in the 6th hour and after the existence of the reservoir, the peak discharge changed to $344 \text{ m}^3/\text{s}$ in the 9th hour. The results of the hydrograph simulation on each re-time are shown in Figures 4, 5 and 6.

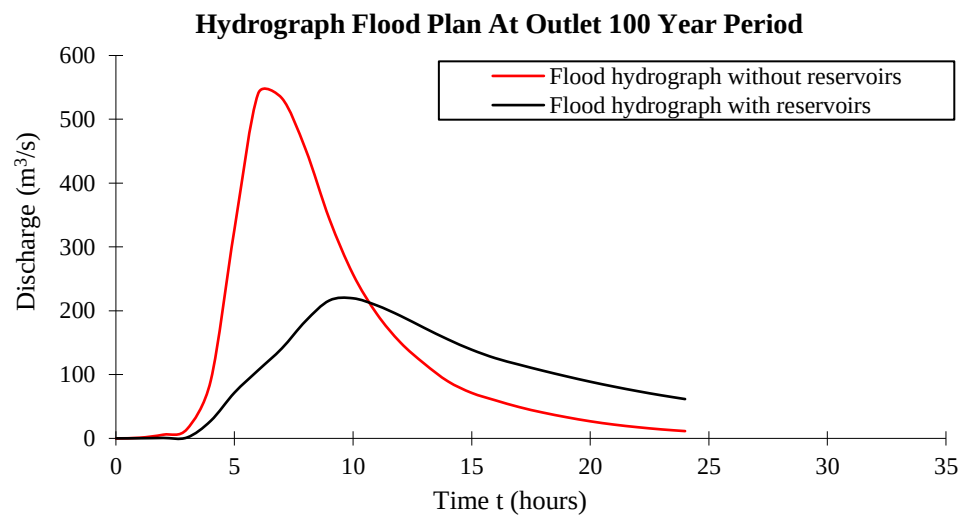


Figure 4. Hydrograph Flood Plan At Outlet Over 100 Years Period

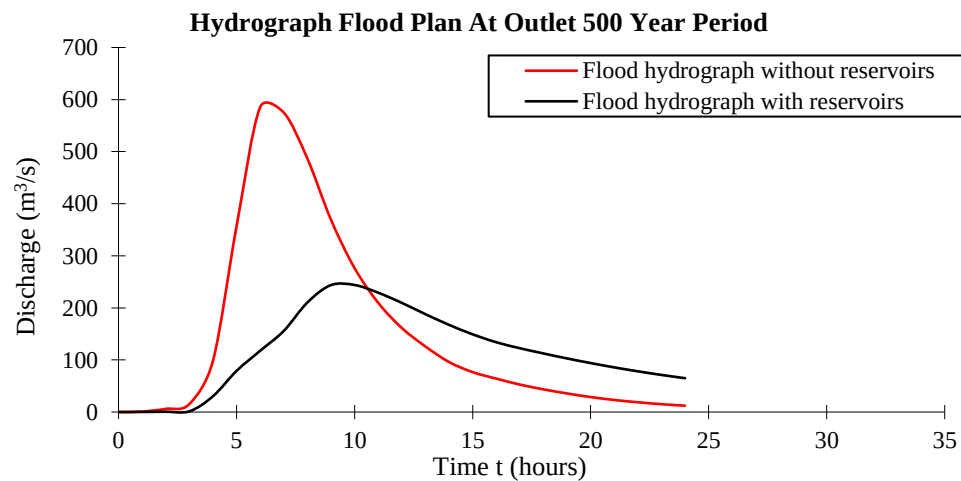


Figure 5. Hydrograph Flood Plan At Outlet Over 500 Years Period

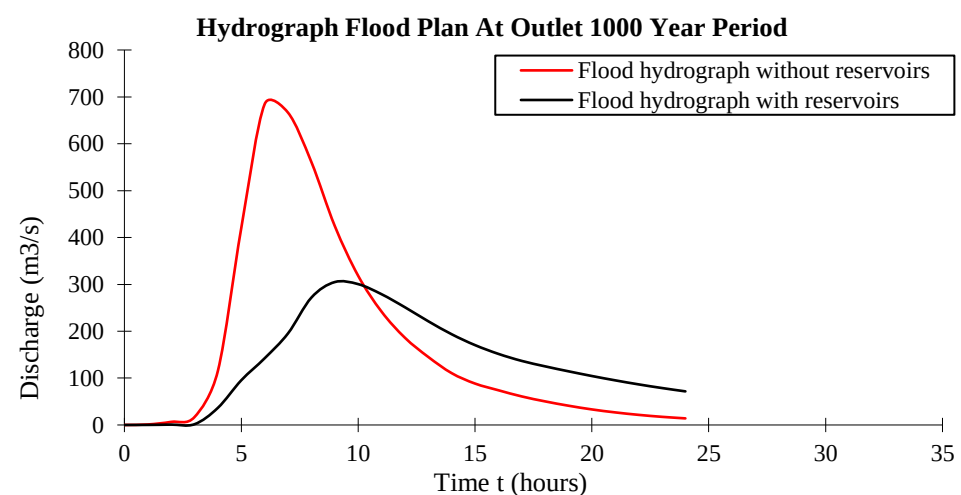


Figure 6. Hydrograph Flood Plan At Outlet Over 1000 Years Period

Simulations executed at the individual outlets of the Pacal and Gongseng reservoirs revealed significant dynamic attenuation across all evaluated return periods. For the 100-year recurrence interval, Pacal Reservoir received a peak inflow discharge of 240,8 m³/s at the 6th hour, while discharging a peak outflow of 77,7 m³/s at the 12th hour. Concurrently, Gongseng Reservoir recorded a peak inflow of 233,2 m³/s at the 7th hour, and releasing a peak outflow of 126,0 m³/s at the 10th hour. Under the 500-year flood event, Pacal Reservoir experienced a peak inflow of 260,1 m³/s at the 6th hour, which was attenuated to a peak outflow of 85,3 m³/s, whereas Gongseng Reservoir absorbed an inflow peak of 251,8 m³/s at the 7th hour and discharged a maximum outflow of 141,3 m³/s at the 10th hour. For the extreme 1,000-year recurrence interval, peak inflow into Pacal Reservoir reached 302,5 m³/s at the 6th hour with a restricted outflow of 107,2 m³/s, while Gongseng Reservoir received 292,3 m³/s at the 7th hour and released 176,7 m³/s at the 9th hour. The Inflow Outflow Hydrograph of Pacal Reservoir and Gongseng Reservoir with 100, 500 and 1000 Return Periods is presented in Figure 7, 8, 9.

Integrated routing through the cascade system demonstrated that the joint presence of both reservoirs substantially suppressed the downstream flood hydrograph at the main watershed outlet, achieving peak discharge reductions of 59,38% (320,9 m³/s), 58,32% (341,4 m³/s), and 55,46% (379,6 m³/s) for the 100-year, 500-year, and 1,000-year return periods, respectively. In addition to discharge magnitude reduction, the impoundments caused notable hydrograph translation and peak time lag extensions. For the 100-year event, Pacal Reservoir reduced the flood peak by 163,1 m³/s and delayed the peak arrival time by 6 hours, while Gongseng Reservoir attenuated the peak by 107,2 m³/s with a 3-hour time lag. For the 500-year scenario, Pacal Reservoir yielded a peak reduction of 174,8 m³/s (6-hour delay) compared to 110,5 m³/s (3-hour delay) at Gongseng Reservoir. Under the 1,000-year scenario, Pacal Reservoir achieved a reduction of 195,3 m³/s (5-hour delay), whereas Gongseng Reservoir provided a reduction of 115,6 m³/s (2-hour delay).

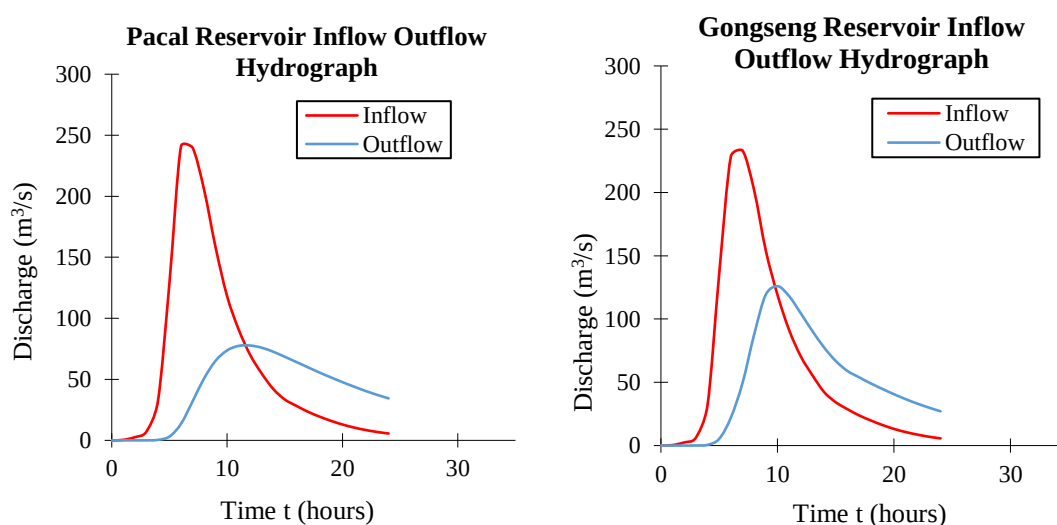


Figure 7. Hydrograph Inflow Outflow Reservoir 100 Years Period

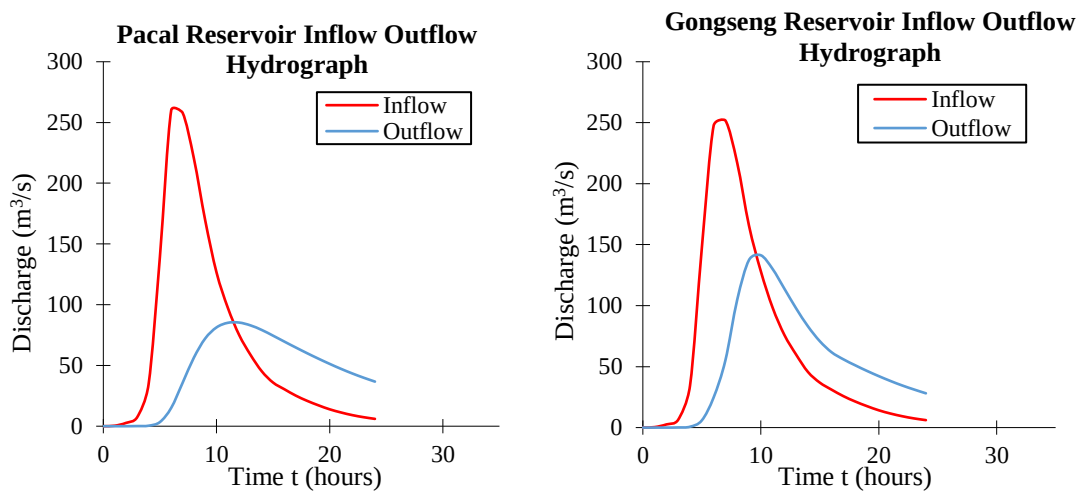


Figure 8. Hydrograph Inflow Outflow Reservoir 500 Years Period

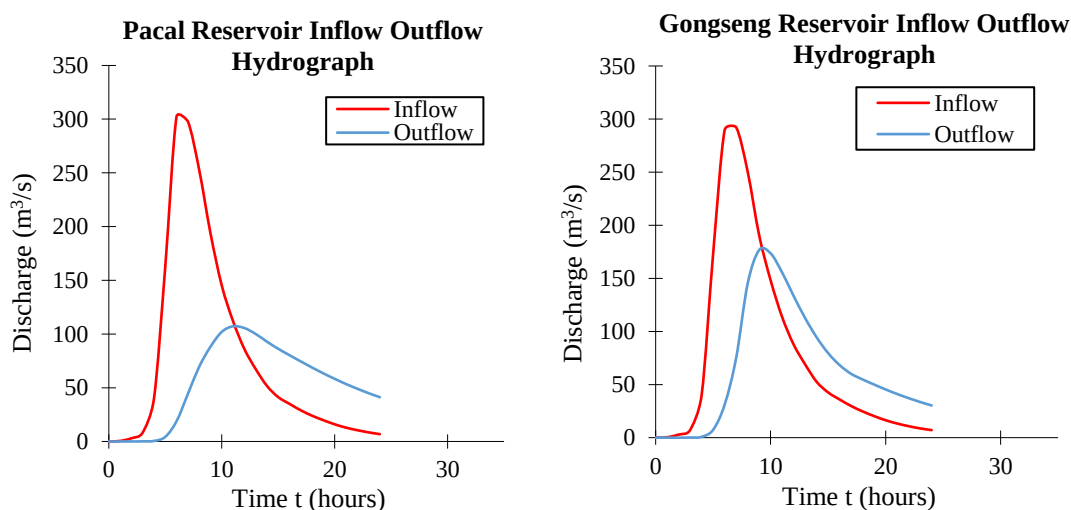


Figure 9. Hydrograph Inflow Outflow Reservoir 1000 Years Period

Hydrological simulation results from the Pacal Watershed provide empirical evidence supporting the theory regarding the role of reservoirs as hydraulic shock absorbers. As explained by Souza et al. (2017) and Bartos and Kerkez (2019), reservoir storage capacity serves to absorb the energy and volume of surface runoff. Simulation findings recording a peak discharge reduction of 55,46% – 59,38% ($320,9 \text{ m}^3/\text{s}$ – $379,6 \text{ m}^3/\text{s}$) along with a peak flood delay of 2 to 6 hours directly prove the hydrograph geometry modification mechanism previously reviewed by Kalra et al. (2023) and Wibowo et al. (2024). Furthermore, this downstream shift in peak arrival time extends the evacuation window for affected communities, aligning with the practical benefits of disaster risk management emphasized by Wang et al. (2023).

This study simultaneously resolves the research gap identified from the works of Subrata and Putuhena (2012) and Wan et al. (2018) concerning the effectiveness of localized multi-reservoir systems. Despite environmental degradation and land-use changes driving flashy hydrological responses with peak discharges occurring as early as the 6th to 7th hours under landscape alterations mapped by Harjono and Widhiastuti (2019) as well as Nada and Sunariya (2025), the integration of

Pacal and Gongseng reservoirs remains reliable in attenuating extreme flood peaks by over 50%. Unlike reservoir systems in continental-scale basins that extend hydrograph transit times to days, the physical characteristics of the Pacal Watershed yield hydrograph attenuation responses occurring on a hourly scale.

This simulation verifies the phenomenon of storage efficiency decay during larger return periods, as cautioned in the study by Evangelista et al. (2025). The decrease in attenuation efficiency from 59,38% for the 100-year event to 55,46% for the 1,000-year event confirms that massive storm volumes gradually consume available surcharge storage capacity. This finding underscores the importance of updating reservoir operating rule curves through pre-release protocols, a structural-operational mitigation strategy to enhance the resilience of disaster-prone areas.

CONCLUSION

The validated HEC-HMS model simulation results demonstrate that the integration of the Pacal and Gongseng reservoirs significantly attenuates extreme flood peak discharges by 55,46% to 59,38% (ranging from 320,9 m³/s to 379,6 m³/s), while simultaneously delaying downstream peak arrival times by 2 to 6 hours across 100-year to 1,000-year return periods. This hydrograph translation provides critical practical implications by extending the evacuation time window for disaster mitigation in Bojonegoro Regency, although the attenuation efficiency gradually declines during massive recurrence events due to the finite availability of surcharge storage capacity. The inherent modeling limitations specifically the omission of long-term sedimentation impacts, baseflow dynamics, and channel routing are recommended to be addressed in further research.

REFERENCES

- Aggarwal, S. P., Barman, D., Kundu, S. S., Kurbah, S., & Das, R. (2025). EO aided comprehensive flood management for the Brahmaputra and Barak river basin in NE India. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-G-2(April), 6–11. <https://doi.org/10.5194/isprs-archives-xxviii-g-2025-63-2025>
- Bartos, M., & Kerkez, B. (2019). Hydrograph peak-shaving using a graph-theoretic algorithm for placement of hydraulic control structures. *Advances in Water Resources*, 127, 167–179. <https://doi.org/10.1016/j.advwatres.2019.03.016>
- Buana, H., Limantara, L. M., Juwono, P. T., & Sholichin, M. (2022). Time Lag Modeling in Modification of Nakayasu Synthetic Unit Hydrograph. *Journal of Hunan University Natural Sciences*, 49(7), 9–17. <https://doi.org/10.55463/issn.1674-2974.49.7.2>
- Buda, A. R., Millar, D. J., Kennedy, C. D., Welsh, M. K., & Wiegman, A. R. H. (2024). Trends in extreme rainfall over the past 55 years suggest springtime subhourly rainfall extremes have intensified in Mahantango Creek, Pennsylvania. *Nature*, 14(1), 1–19. <https://doi.org/10.1038/s41598-024-79196-3>
- Cirella, G. T., Iyalomhe, F. O., & Adekola, P. O. (2019). Determinants of flooding and strategies for mitigation: Two-year case study of Benin city. *Geosciences (Switzerland)*, 9(3), 1–15. <https://doi.org/10.3390/geosciences9030136>
- Erena, S. H., & Worku, H. (2018). Flood risk analysis: causes and landscape based mitigation strategies in Dire Dawa city, Ethiopia. *Geoenvironmental Disasters*, 5(1). <https://doi.org/10.1186/s40677->

018-0110-8

- Evangelista, G., Bertola, M., Blöschl, G., & Claps, P. (2025). Non-Linear Influence of Reservoir Initial Condition on Flood Reduction. *Journal of Flood Risk Management*, 18(4), e70142. <https://doi.org/10.1111/jfr3.70142>
- Ferdian, D., Saggaff, A., & Sarino. (2020). Efektifitas Pengendalian Banjir dengan Embung: Studi Kasus Taman Firdaus Universitas Sriwijaya. *Cantilever: Jurnal Penelitian dan Kajian Bidang Teknik Sipil*, 9(1), 57–62. <https://doi.org/10.35139/cantilever.v9i1.39>
- Ginting, B. M., Lidyana, P., Christopher, C., Yudianto, D., & Yuebo, X. (2023). Comparison of flood hydrograph prediction between synthetic unit hydrograph methods and rain-on-grid model for Katulampa watershed, Indonesia. *Acta hydrotechnica*, 36(64), 81–94. <https://doi.org/10.15292/acta.hydro.2023.05>
- Hamdan, A. N. A., Almuktar, S., & Scholz, M. (2021). Rainfall-Runoff Modeling Using the HEC-HMS Model for the Al-Adhaim River Catchment, Northern Iraq. *Hydrology*, 8(2), 58. <https://doi.org/10.3390/hydrology8020058>
- Harjono, H., & Widhiastuti, Y. (2019). Analisa Hidrologi dan Hidrolika Pada Daerah Aliran Sungai (DAS) Kali Pacal Bojonegoro. *Rekayasa Sipil*, 13(1), 16–23. <https://doi.org/10.21776/ub.rekayasasipil.2019.013.01.3>
- Indarto. (2018). *Hidrologi Metode Analisis dan Tool untuk Interpretasi Hidrograf Aliran Sungai* (S. B. Hastuti (ed.)). Bumi Aksara.
- Kalra, S., Madguni, O., & Rana, D. (2023). Sustainable Waste Management of Man-Made Dams and Reservoirs. In *Advances in Waste Management* (hal. 141–153). Springer Singapore. https://doi.org/10.1007/978-981-19-7506-6_11
- Maulana, N. K., & Sutopo, Y. (2020). Design Flood Discharge of 50 Years in Garang River Using Nakasayu Synthetic Unit Hydrograph Method. *Jurnal Teknik Sipil dan Perencanaan*, 22(2), 146–151. <https://doi.org/10.15294/JTSP.V22I2.26847>
- Msaddek, M., Kimbowa, G., & Garouani, A. El. (2020). *Hydrological Modeling of Upper OumErRabia Basin (Morocco), Comparative Study of the Event-Based and Continuous-Process HEC-HMS Model Methods*. 159–184. <https://doi.org/10.4236/cweee.2020.94011>
- Mulyanti, H., Harjono, H., & Rendra, M. I. (2020). Penurunan Intensitas Hujan Ekstrem di Bengawan Solo Hilir dan Hubungannya dengan ENSO. *Jurnal Ilmu Lingkungan*, 18(1), 73–81. <https://doi.org/10.14710/jil.18.1.73-81>
- Nada, F. M. H., & Sunariya, M. I. T. (2025). The impact of land cover change on runoff coefficient at Upper Garang Watershed, Jawa Tengah Province, Indonesia. *IOP Conference Series: Earth and Environmental Science*, 1438(1), 012021. <https://doi.org/10.1088/1755-1315/1438/1/012021>
- Pabi, O., Egyir, S., & Attua, E. M. (2021). Flood hazard response to scenarios of rainfall dynamics and land use and land cover change in an urbanized river basin in Accra, Ghana. *City and Environment Interactions*, 12, 100075. <https://doi.org/10.1016/j.cacint.2021.100075>
- Prastica, R. M. S., Widyatmoko, A., & Kurniawan, R. (2021). Mitigasi Banjir Struktural Menggunakan Model Hec-Ras Dan Geo-Studio Pada Wilayah Sungai Toba-Asahan, Sumatera Utara. *Teras Jurnal*, 11(2), 399. <https://doi.org/10.29103/tj.v11i2.519>
- Rahmadani, S., Harahap, R., Yuzni, S. Z., Rani, C. M., Tinov, N., Waruwu, J. A., & Rahmadani, S. S. (2024). Hydrological Study of Deli River Flood Discharge Using the HSS Nakayasu Model. *Journal of Physics: Conference Series*, 2908(1), 012016. <https://doi.org/10.1088/1742->

6596/2908/1/012016

- Saltalippi, C., Corradini, C., Dari, J., & Morbidelli, R. (2022). Rainfall and development of floods. In *Rainfall* (hal. 351–366). Elsevier. <https://doi.org/10.1016/b978-0-12-822544-8.00015-9>
- Sarkar, A., & Drissia, T. K. (2024). Integrated Reservoir Simulation and Hydrological Modelling for Optimised Reservoir Operations in Kerala, India. In A. Agarwal, B. Yadav, M. Nema, M. Sharma, & A. Kumar (Ed.), *Towards Water Circular Economy* (hal. 50–60). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-60436-2_4
- Soliman, A. H. (2022). Development of Rainfall Design Storm Hyetographs for Al-Quassim Region - Kingdom of Saudi Arabia. *International Journal of Engineering Trends and Technology*, 70(1), 362–372. <https://doi.org/10.14445/22315381/IJETT-V70I1P240>
- Souza, D. N. de, Studart, T. M. de C., Lima Neto, I. E., & Campos, J. N. B. (2017). Flood damping by reservoirs: proposition of a graphical parametric method. *RBRH*, 22. <https://doi.org/10.1590/2318-0331.0217170002>
- Subrata, O., & Putuhena, W. M. (2012). Pengelolaan Banjir Berbasis Masyarakat (Studi Kasus : Kabupaten Bojonegoro) Community-Based Flood Management (Case Study : Kabupaten Bojonegoro). *Jurnal Sumber Daya Air*, 8, 125–140.
- Sukerte, N. (2022). Rekayasa Pengendalian Banjir Dan Konservasi Sumber Daya Air Pada Daerah Hulu. *Jurnal Profesi Insinyur Universitas Lampung*, 3(2), 78–84. <https://doi.org/10.23960/jpi.v3n2.84>
- Wan, X., Hua, L., Yang, S., Gupta, H. V., & Zhong, P. (2018). Evaluating the Impacts of a Large-Scale Multi-Reservoir System on Flooding: Case of the Huai River in China. *Water Resources Management*, 32(3), 1013–1033. <https://doi.org/10.1007/s11269-017-1852-x>
- Wang, J., Xu, J., & Kong, D. (2023). Time-Lagged Response of Streamflow in the Lower Yellow River to the Water Regulation by Xiaolangdi Reservoir: Implication for Efficient Water Supply. *Water*, 16(1), 78. <https://doi.org/10.3390/w16010078>
- Wibowo, A. A., Sangkawati, S., & Nugroho, H. (2024). Kajian Kapasitas Pelimpah dan Terowongan Konduit Bendungan Sawangan dalam Mereduksi Debit Puncak Banjir. *Al Qalam: Jurnal Ilmiah Keagamaan dan Kemasyarakatan*, 18(3), 2084–2098. <https://doi.org/10.35931/aq.v18i3.3313>