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Runoff Hydrograph Analysis of HEC-RAS 2D Flow Hydrodynamics Meteorological Rain-on-Grid on Observed Watershed: A Case Study of Wiroko Sub-Watershed

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***Abstract*—In contemporary hydrological analysis, numerical models have emerged as an alternative solution for water resources planning and management, particularly in forecasting extreme events and mitigating disaster risks. HEC-RAS 2D flow hydrodynamics enables the modeling of rainfall with input from meteorological boundary condition data. Precipitation within the studied watershed can be modeled as point rainfall or area-averaged rainfall in the rain-on-grid feature of HEC-RAS 2D flow hydrodynamics. In this study, the HEC-RAS 2D flow model utilizes the diffusion wave equations (DWE) for simulating unsteady flow routing. When modeling a complex watershed, the 2D hydrodynamics model has become a viable alternative, especially concerning the watershed's physical characteristics. This study aims to assess the reliability of HEC-RAS 2D flow hydrodynamics and compare its results with the hydrograph data from the observed watershed in the Wiroko Sub-Watershed of the upper Wonogiri Dam. In this research, extreme rainfall events of 100 mm in the first hour are simulated and compared with the hydrograph data from the observed watershed. Based on the numerical model results in the Wiroko Sub-Watershed, it was determined that conforming to the land use with a Manning roughness value of 0.12 (designated as developed area-medium intensity) resulted in a peak discharge (Qp) difference of 0.8%. Meanwhile, the time to peak (Tp) value exhibited a discrepancy of 1.93 hours longer between the numerical model and the observed hydrograph.**

***Keywords*— Runoff hydrograph; HEC-RAS 2D; flow hydrodynamics; meteorological data; Wiroko sub-watershed.**

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I. INTRODUCTION

The hydrological analysis plays a crucial role in predicting extreme events and managing water resources engineering in Indonesia. In flood forecasting analysis within a watershed based on the unit hydrograph heavily relies on the availability of hourly rainfall data and automatic water level recorder (AWLR) data [1]. However, in Indonesia, there is still a limitation in hourly data availability, making it nearly impossible to find observed hydrograph data in almost all watersheds. Several synthetic unit hydrographs (SUH) theories have been developed for use in various water infrastructure planning projects in Indonesia to address this issue. Furthermore, accurately estimating hydrographs is vital for effective flood management and infrastructure planning. Using synthetic unit hydrographs has proven to be a valuable tool in areas where observed data is limited [2]. By employing these theoretical models, informed decisions are facilitated, enhancing the resilience of water-related projects in the region.

Empirical formulas related to synthetic unit hydrographs developed in Indonesia [3] include Gamma 1, derived from 30 watershed areas in Java Island. ITS 1 SUH adopts the Delay-Storage method, expressed as a single-curve hydrograph equation. ITB 1 and 2 SUH, with simple parameters of peak discharge equations, are formulated based on mass conservation equations. Limantara SUH was developed in 2008 based on various watershed areas in Indonesia (Java, Kalimantan, Bali, and Lombok) with an area (A) ≤ 5000 km2 and ITS 2 SUH was developed in 8 watersheds in Central Sulawesi province.

Meanwhile, several theories of synthetic unit hydrographs that are also frequently used in hydrological analysis for planning and managing water resources engineering in Indonesia include Snyder, SCS hydrograph, and Nakayasu SUH. Snyder SUH (1938) put forth several empirical formulas based on watershed parameter data in the United

States, ranging in size from 30 km² to 30,000 km². Currently, Nakayasu SUH is the most commonly used in planned flood analysis in Indonesia, which was developed based on the characteristics of watershed areas in Japan and was initially applied in Indonesia in the water infrastructure planning in the Brantas watershed during the 1970s. Its widespread adoption underscores its efficacy and adaptability in the Indonesian context, reaffirming its significance in contemporary water resource engineering practices.

In addition to empirical method calculations, the hydrological analysis approach with numerical models is currently constructive for researchers. One of the software that can model hydrographs is HEC HMS [4]. HEC-HMS is a comprehensive hydrologic modeling system meticulously crafted to replicate all the hydrologic processes inherent to watershed systems. This software encompasses various hydrologic analysis techniques, spanning infiltration, unit hydrographs, and hydrologic routing to the requisite procedures for continuous simulation, such as evapotranspiration, snowmelt, and soil moisture accounting. Currently, HEC-HMS 2D allows for the simulation of complex hydraulic scenarios that cannot be accurately simulated using hydrologic routing. In addition to HEC-HMS, and currently HEC-RAS 2D [5],[6] also features meteorological input that can be used in extreme flood event analysis. The 2D Diffusion Wave transform is used by the two software to more accurately route water within the area of interest during large floods. Compared to HEC-HMS research, HEC-RAS 2D flow hydrodynamic meteorological data in Indonesia has yet to be extensively studied for watershed case studies as it is still relatively new. Meteorological data can be entered into HEC-RAS as gridded or point-gauge data.

Related studies on the capabilities of HEC-RAS 2D flow hydrodynamics in modeling runoff hydrographs include the following: [7] investigates the application of HEC-RAS 2D rain-on-grid simulations for the measurement and modeling of event-based environmental flows and evaluates the sensitivity of model results to crucial input parameters and assumptions. [8],[9] presents a benchmarking study evaluating the accuracy of HEC-RAS 2D for storm-event hazard assessment and addresses whether HEC-RAS 2D, a widely used hydraulic modeling tool, is sufficiently accurate for predicting hazards during storm events. Through rigorous benchmarking and analysis, this research provides valuable insights into the capabilities and limitations of HEC-RAS 2D for storm-event hazard assessment. [10] employs the performance synthetic unit hydrograph, HEC-HMS, and HEC-RAS 2D unsteady flow rain-on-grid model to conduct a comprehensive flood hydrograph analysis in the Keser watershed of East Java. This study requires further investigation for Time of Peak (Tp) values due to variability between the Hec-Ras model and SUH calculation. The runoff hydrograph analysis conducted using HEC-RAS 2D hydrodynamics yielded results that closely approximated those obtained from the physical model of the rainfall simulator [2]. In a recent study conducted by [11], a comprehensive analysis of the correlation between rain-on-grid simulations and spatial resolution in 2D hydrodynamic modeling using HEC-RAS revealed that the runoff is notably delayed at the catchment outlet for coarser grids from 10 m mesh.

This study aims to assess the reliability of HEC-RAS 2D flow hydrodynamics and compare its results with the hydrograph data from the observed watershed in the Wiroko Sub-Watershed of the upper Wonogiri Dam. The observed hydrograph data, to be used for comparison with HEC-RAS 2D meteorological data, was obtained from previous research by [1]. Thus, it is expected that the performance and reliability of HEC-RAS 2D will be determined compared to observed data.

II. Materials and Methods

A. Study Area

The Wonogiri Reservoir encompasses a comprehensive catchment area of approximately 1,343 square kilometers, comprising ten distinct sub-watersheds. The Wiroko watershed (Fig. 1) ranks the second largest, covering an estimated 183.9 square kilometers [12]. The Wonogiri Dam, also called the Gajah Mungkur Dam, serves various functions, including flood control, provision of irrigation water, a 12.4 MW hydroelectric power plant (HPP), and a source of raw water supply.

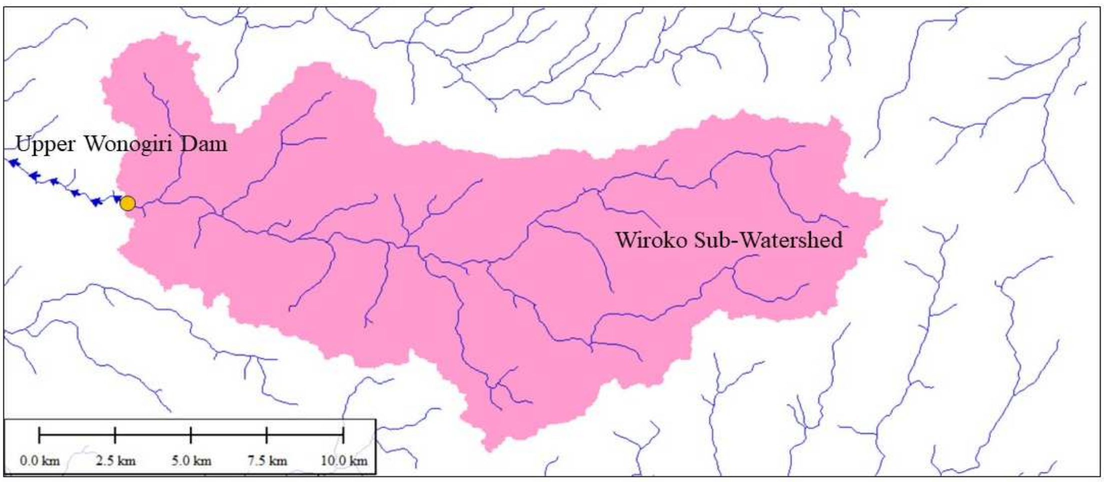

Fig. 1 Wiroko sub-watershed in the upper Wonogiri Dam of Central Java

B. Unit Hydrograph

The unit hydrograph is a pivotal hydrological concept in estimating a watershed's runoff or streamflow reaction to specific precipitation within a defined timeframe [13]. It is a graphical representation illustrating the temporal distribution of direct runoff from a standardized depth of adequate rainfall. This hydrograph represents the direct runoff resulting from a uniform rainfall application, typically at 1 inch, 1 centimeter, or 1-millimeter depth, spread evenly across the watershed and occurring uniformly over a specified duration. Its primary aim is to offer a simplified and efficient means of anticipating a watershed's response to diverse rainfall scenarios, significantly impacting flood prediction, reservoir design, and water resource management. The foundational principles of the unit hydrograph are rooted in linear systems theory, adhering to principles such as superposition and proportionality. The volume of water encapsulated in the unit hydrograph must match the excess rainfall. By definition, since a rainfall excess of 1cm is considered, the area under the unit hydrograph correlates to a volume represented by a 1cm depth of water across the catchment area.

The unit hydrograph (Fig. 2) operates on the premise of a consistent time of concentration, signifying the duration for water to traverse from the watershed's farthest point to the outlet, irrespective of fluctuations in rainfall events [14]. Parameters within the hydrograph, encompassing peak time (Tp), base time (Tb), peak discharge (Qp), rising limb, and recession limb, elucidate the watershed's characteristics in response to rainfall input.

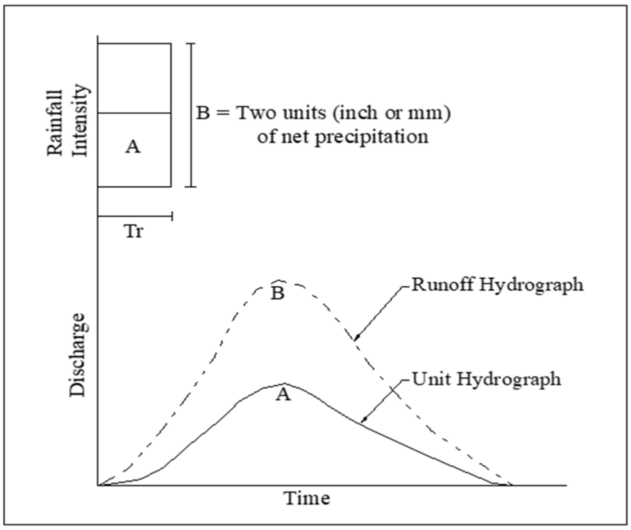

Fig. 2 The unit hydrograph derived from the runoff hydrograph

A runoff hydrograph is a graphical representation depicting the flow rate of a stream or river in response to precipitation over time (Fig. 2). It's derived by multiplying the unit hydrograph's ordinate by the corresponding ordinate of the excess rainfall hyetograph and summing these products for each time interval [15]. This resulting hydrograph illustrates the streamflow variation over time, highlighting the peak flow rate coinciding with the maximum excess rainfall occurrence. Studies concerning runoff hydrographs are presently essential in forecasting extreme events [16], [17] and managing water resources, including risk mitigation in Indonesia [18], [19].

This hydrograph is a crucial tool in hydrology. It facilitates predictions regarding the impact of precipitation on streamflow, estimates peak flow rates, time to peak flow, and total runoff volume from specific precipitation events, and aids in the design of hydraulic and flood control structures. The unit hydrograph delineates the catchment's response to a unit depth of excess rainfall, while the excess rainfall hyetograph illustrates the temporal distribution of this excess rainfall.

Observational hydrograph data was obtained from a prior study conducted by Sulistyowati [1]. The findings revealed that the observed unit hydrograph in the Wiroko sub-watershed displayed a peak discharge (Qp) occurring at 9.15 hours, with a time to peak of 3 hours. The time base (Tb) in the Wiroko sub-watershed was also recorded as 22 hours (Fig. 3).

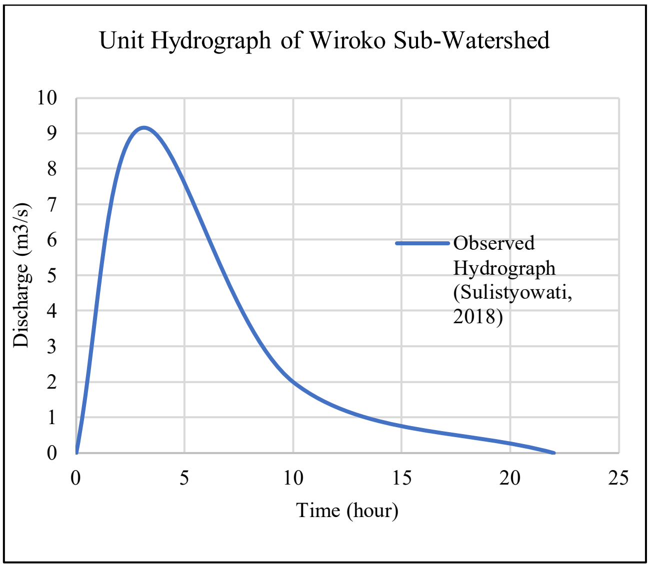

Fig. 3 Observed unit hydrograph of Wiroko sub-watershed [1]

C. HEC-RAS 2D Flow Hydrodynamics Meteorological Data

The analysis of runoff hydrographs in this study will utilize the computational model HEC-RAS 2D flow v6.3 [5], [6], developed by the US Army Corps of Engineering. HEC-RAS demonstrates proficiency in simulating steady one-dimensional flow and various forms of unsteady one and two-dimensional flow [20], integrating meteorological input data like precipitation, evapotranspiration, and infiltration data. The HEC-RAS 2D hydrodynamics tool notably presents a unique advantage in accurately replicating a stream or river's response to precipitation events through rain-on-grid simulations [7]. This capability allows for the generation of runoff hydrographs, crucial in predicting the impact of precipitation on streamflow and designing hydraulic structures and flood control measures.

Moreover, the HEC-RAS 2D hydrodynamics accommodates both 1D and 2D modeling and their combined application, enabling analyses of larger river systems and areas requiring enhanced hydrodynamic precision. Additionally, its ability to construct detailed hydraulic property tables for computational cells and cell faces based on the underlying terrain enhances its utility. Often referred to as a "high-resolution sub grid model," this feature contributes to a more accurate depiction of terrain and water flow patterns

[5]. The HEC-RAS 2D flow model conducts simulations of unsteady flow using either the Diffusion Wave Equation (DWE) [21]–[23] or the Shallow Water Equation (SWE) [24]–[26], with the Eulerian-Lagrangian method (SWE-ELM) as the default formula in Hec-Ras [27], [28]. The general equations utilized involve mass and momentum conservation, approximated from the Diffusion Wave or Shallow Water Equation in the 2-dimensional x and y coordinates. The mass conservation equation is presented below:

$$\frac{\partial H}{\partial t} + \nabla \cdot hV + q = 0 \quad (1)$$

where the variable "t" signifies time, "V" denotes the velocity vector, and "q" stands for the external contribution or flux term (source/sink). The water level elevation "H" is derived from the source as follows:

$$H(x, y, t) = z(x, y) + h(x, y, t) \quad (2)$$

In the given scenario, "z" signifies to the channel bed elevation, and "h" signifies the water level. The equation for momentum conservation is utilized as depicted in the following formula.

$$\frac{\partial V}{\partial t} + V \cdot \nabla V = -g\nabla H + v_t \nabla^2 V + c_f V + fk \times V \quad (3)$$

In the provided context, $\boldsymbol{v_t}$ represents the horizontal eddy viscosity, c_f denotes the coefficient of friction, and f indicates the Coriolis factor. In HEC-RAS v6.3, a sub-grid functionality is integrated into its computational techniques. The calculation of reservoir volume in each cell (grid) considers the topographical conditions at a finer level of detail. As a result, the discharge analysis is derived from this more detailed topographic data, leading to enhanced accuracy even when employing a coarser computational cell with heightened roughness.

A 2D model in HEC-RAS necessitates terrain data and incorporates a designated 2D Flow Area comprising cells of varying sizes and shapes. Beyond this, HEC-RAS permits the inclusion of hydraulic structures and the integration of 1D elements, like storage areas, into a 2D model. It's crucial to note that all 2D hydraulic models must be executed as unsteady, and their run times are notably longer than 1D models. In computational terms, while 1D models employ the St. Venant equations in one dimension, 2D models solve these equations across two dimensions, specifically employing the St. Venant equations of Conservation of Mass and Conservation of Momentum [29].

For computational expediency, HEC-RAS defaults to using the diffusion wave equation in 2D modeling, favoring speed over complexity. This equation, although a simplified representation, enables faster model execution. However, the program also allows users to opt for the full dynamic conservation of momentum equations, albeit resulting in longer run times. The Diffusion Wave Equation, the default choice, facilitates quicker computations, particularly suited for gradual flow variations in regions with moderate to steep slopes. Though less accurate than the complete dynamic conservation of momentum equations, the DWE [30] adequately models numerous scenarios. Nonetheless, users can opt for the whole dynamic conservation of momentum equations for enhanced precision if necessary.

In Hec-Ras 2D Flow Hydrodynamics, the Manning roughness coefficient (n) is a pivotal parameter. Within HEC-RAS 2D modeling, these coefficients precisely correspond to land cover types, attributing to the quantification of energy dissipation caused by friction during overland flow or potential channel flow within the 2D domain. The determination of Manning's roughness coefficients (n) for 2D flow is influenced by many factors, encompassing land surface characteristics such as type, texture, permeability, impermeability, and the depth of the 2D flow. While extensive research has explored Manning's n values within the confines of 1D channels, exploring these values in the context of the 2D domain still needs to be expanded. Notably, the HEC-RAS 2D User's Manual provides references elucidating Manning's roughness values tailored to diverse land cover types, detailed in Table 1.

The Manning roughness values in this study are adjusted to the land use in the Wiroko sub-watershed. For areas developed with medium intensity and 40% imperviousness, the Manning value (n) is set at 0.12. Subsequently, this Manning value will influence the magnitude of outflow discharge (Q) and the time of peak (Tp) in the runoff hydrograph graph.

In numerical models using HEC-RAS 2D hydrodynamics with meteorological rainfall input in the HEC-RAS software, rainfall can be set uniformly and distributed evenly throughout the watershed area, resulting in discharge hydrographs derived from its output. The rainfall input consists of point rainfall that affects the watershed, followed by the consideration of average rainfall across the watershed area, assumed to be uniformly distributed across the entire watershed and distributed using Thiessen polygons. This input is readily available in the HEC-RAS 2D hydrodynamics software.

TABLE I
MANNING'S ROUGHNESS COEFFICIENT RECOMMENDATIONS IN HEC-RAS 2D USER'S MANUAL [4]

ID	Name	Mannings (n)	Percent Impervious
0	No Data	0.035	0
43	Mixed Forest	0.12	0
41	Deciduous Forest	0.1	0
21	Developed, Open Space	0.035	0
42	Evergreen Forest	0.15	0
11	Open Water	0.035	100
52	Shrub/Scrub	0.05	0
81	Pasture/Hay	0.045	0
71	Grassland/Herbaceous	0.04	0
82	Cultivated Crops	0.05	0
22	Developed, Low Intensity	0.08	20
95	Emergent Herbaceous Wetlands	0.045	75
90	Woody Wetlands	0.07	50
23	Developed, Medium Intensity	0.12	40
24	Developed, High Intensity	0.15	60
31	Barren Land Rock/Sand Clay	0.03	0

III. RESULTS AND DISCUSSION

In this study, numerical modeling was conducted using Hec-Ras 2D unsteady flow hydrodynamics v6.3, wherein meteorological data in rain-on-grid simulations were employed as input for rainfall height. In this research, effective rainfall events of 100 mm in the first hour are simulated and then compared with the hydrograph data from the observed watershed. The initial step in this Hec-Ras 2D modeling process involved importing the Ras Mapper from the previously generated geotiff file using a global mapper. A projection setting was necessary for the watershed data input in the RAS Mapper to ensure compatibility with Hec-Ras 2D. When uploading the GeoTIFF document from Global Mapper, a resolution of 1/1000 was selected to provide the highest quality and accuracy of the input within the Ras Mapper.

In the Geometry input, the initial step involves delineating the 2D flow area and then setting the mesh size for this numerical model to a relatively small scale of 50 x 50 meters. This results in a total of 84,299 meshes. Subsequently, break lines representing the main river are delineated, followed by adding boundary condition lines (BC lines) at the downstream/outlet of the Wiroko sub-watershed. The input for the boundary conditions is set to a standard depth of 0.04, adjusted by the average terrain slope in the Wiroko sub-watershed. As for meteorological data, the rainfall input involves specifying point rainfall data, with the model assuming a uniform distribution of rainfall across the entire watershed using Thiessen polygons. The rainfall data is tested with specific values, ensuring that the resulting volume aligns with a practical rainfall value of 100 mm when divided by the area of the Wiroko sub-watershed (183.9 km²). The final step in the numerical modeling with Hec-Ras 2D involves computational settings, with the time step value set to 1 minute, and the simulation is carried out utilizing the 2D diffusion wave equation (DWE). The simulation results can be assessed regarding volume error percentage and the shape of the output discharge hydrograph. The output of water depth values of Wiroko sub-watershed in HEC-RAS 2d unsteady flow hydrodynamics is depicted in Fig. 4.

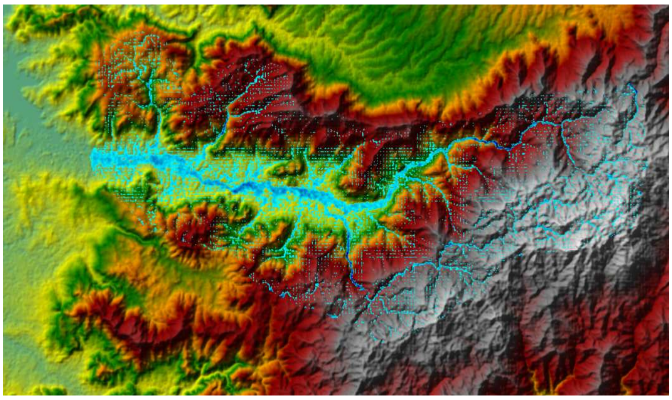

Fig. 4 The output of water depth values of Wiroko sub-watershed in HEC-RAS 2D unsteady flow hydrodynamics

The results of the numerical modeling using HEC-RAS 2D unsteady flow, coupled with meteorological data obtained from rain-on-grid simulations with a targeted Manning's roughness coefficient of 0.12 for the developed area (medium intensity), yielded a peak discharge value of 922 m³/second (Fig. 5). Additionally, the multiplication of the ordinate of the unit hydrograph by the corresponding ordinate of the excess rainfall hyetograph (100 mm) resulted in an observed runoff hydrograph value of 915 m³/second. With these findings, the comparison between the peak discharge (Qp) for observed data and the numerical model using HEC-RAS 2D flow demonstrated a close alignment, with a percentage error of merely 0.8% (Fig. 4). However, a notable disparity persists in the Time of Peak (Tp) values. The numerical model using HEC-RAS 2D yielded a Tp of 4.93 hours, 1.93 hours later than the observed data, where Tp was determined to be 3 hours. Consequently, further research is warranted, particularly concerning the Time of Peak (Tp) and Time of Concentration (Tc), to ascertain the reliability of the HEC-RAS 2D model. This result aligns with the research of [11][31] that the runoff is significantly delayed at the catchment outlet (Fig.5).

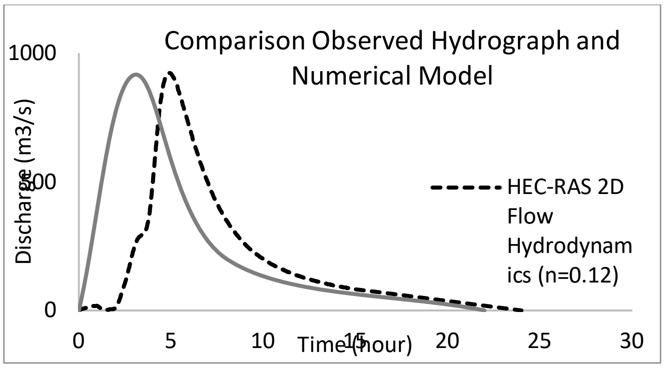

Fig. 5 The comparison results of the observed runoff hydrograph and HEC-RAS 2D numerical model hydrograph in the Wiroko sub-watershed

The comparison of runoff hydrograph volumes from observed watershed and numerical model using HEC-RAS 2D hydrodynamic rain-on-grid meteorological data for a 100 mm effective rainfall height can be observed in Table 2 below. The calculation results of the runoff hydrograph volume between the observed hydrograph yielded a value of 18.53 million m^3, while using HEC-RAS 2D hydrodynamic, a volume of 17.47 million m^3 was obtained, resulting in a difference of 0.94% in the runoff hydrograph volume between the observed watershed and the numerical model.

TABLE II
COMPARISON OF RUNOFF HYDROGRAPH VOLUME IN OBSERVED WATERSHED AND NUMERICAL MODEL OUTPUT

Flood Hydrograph	Time of peak (Tp)	Peak Discharge (Qp)	Volume of Runoff (VRH)
	(hour)	(m^3/s)	(m^3)
Observed Data	3	915	18533000
HEC-RAS 2D	4.93	922	17472050

Fig. 5 shows that the numerical model using HEC-RAS 2D hydrodynamic with 100 mm effective rainfall meteorological input yielded a peak discharge (Qp) value close to the observed hydrograph. However, the numerical model of HEC-RAS resulted in a delayed peak time (Tp) of 1.93 hours compared to the observed hydrograph. This delay is due to the flat portion of the hydrograph curve in the numerical model at the beginning of the rising limb, which lasts for about 1.6 hours, causing the nearest area to the outlet to have no direct effect on the runoff hydrograph. This phenomenon requires further investigation to determine if it is due to the DEM resolution in RAS Mapper, where there are depressions where water still fills up, resulting in a delay. Eliminating this delay would bring the time of peak (Tp) closer to the observed data (Fig. 6).

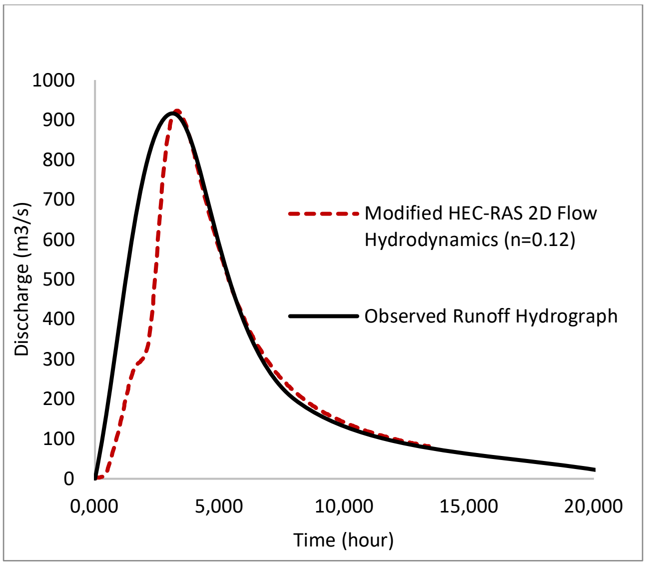

Fig. 6 The comparison between the observed runoff hydrograph and the modified HEC-RAS 2D numerical model hydrograph in the Wiroko sub-watershed

IV. CONCLUSION

This study found the results of the runoff hydrograph reliability model for extreme rainfall events using HEC-RAS 2D flow hydrodynamics meteorological rain-on-grid. The numerical modeling using HEC-RAS 2D, coupled with rain-on-grid simulations and a Manning's roughness coefficient of 0.12, yielded a peak discharge value of 922 m^3/second. The observed runoff hydrograph value obtained through this method closely matched the peak discharge for observed data (915 m^3/second), with a low percentage error of 0.8%

A significant discrepancy was observed in the Time of Peak (Tp) values. The HEC-RAS 2D model indicated a Tp of 4.93 hours, contrasting with the observed data which showed a Tp of 3 hours. This calls for further investigation, particularly regarding Time of Peak (Tp) and Time of Concentration (Tc), to validate the reliability of the HEC-RAS 2D model. The numerical model of HEC-RAS showed a delayed time of peak (Tp) by 1.93 hours compared to the observed hydrograph, which is attributed to the flat portion of the hydrograph curve at the beginning of the rising limb, lasting for about 1.6 hours, and further investigation is needed to determine if this is due to the DEM resolution in RAS Mapper, and eliminating this delay would bring the time of peak (Tp) closer to the observed data.

HEC-RAS 2D Hydrodynamics supports rain-on-grid modeling utilizing meteorological rainfall data employing the diffusion wave equation (DWE) approach, capable of simulating runoff hydrographs for extreme events. However, further adjustments concerning Manning roughness values associated with land use within the watershed are still necessary. Further studies focusing on 2D Hydrodynamic rain-on-grid techniques could be conducted to delve deeper into this feature within HEC-RAS in future research.

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