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Sensitivity Analysis of Rainfall-Runoff Model in Malino Sub-Watershed

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***Abstract*— Overtime, science has been developing and trying to use modelling system in the management of hydrology. In this paper, we present a sensitivity analysis for the HEC-HMS rainfall-runoff model. Sensitivity analysis is used to determine the parameter which most influences the result of the model. The main objective of this research is to investigate the sensitivity of parameter in model and to analyze the influence of the graph types used for unit hydrograph. In addition, we also compare the result of lumped and semi-distributed models based on stream order to analyse a common watershed issue. This study will make a model of rainfall-runoff using a sub-catchment distribution method based on stream order. ArcGIS and HEC-HMS were used as softwares to process data. The data needed in this study come from secondary data sourced from various sources. The data that will be processed first is DEM (Digital Elevation Model). DEM used in this study was sourced from the Geospatial Information Agency or commonly referred to as DEMNAS (The National DEM). ArcGIS will process geospatial data in the form of DEM which data results can be used directly to make model in HEC-HMS. Then, the results of the rainfall-runoff model will be calibrated using observed unit hydrograph. From the result of sensitivity analysis, it was concluded that impervious is the most sensitive parameter. Moreover, this paper also can be used as guidelines for use in rainfall-runoff modelling on HEC-HMS.**

***Keywords*— sensitivity; modelling; rainfall-runoff; stream order; HEC-HMS.**

I. INTRODUCTION

Over time, science has been developing and trying to use a modelling system in the management of hydrology. Hydrological modelling is used to explain the process of changing rainfall into a river discharge by considering the characteristics of a watershed. This model can simplify the hydrological system so that what is needed in the system can be determined by simply entering the required parameters [1]. Rainfall-runoff modelling is an example of a hydrological model. This rainfall-runoff model can be used as a tool to monitor and evaluate discharge by the existing surface water resources [2].

The development of methods in processing the new rainfall-runoff model is still very much needed. The development of the methods is expected to produce results suitable with observed conditions. The concept of a lumped models and semi-distribution models is one of the basic classifications of model types applied to hydrological models [3]. In general, the hydrological model often created is still in lumped model form in which the geographical and physical parameters of a watershed are still represented by one value parameter. In fact, in the hydrological model, a watershed can be divided into parts or often called a semi-distribution model. Unlike the lumped model, the parameters owned by the semi-distribution model in each sub-catchment are different [4]. In this case, the number of sub-catchments affects the simulation results. The geographical and physical characteristics of different watersheds will change the hydrological response of the watershed. It causes the lumped and semi-distribution model will produce different hydrograph simulation results [5]. The different hydrological responses between the lumped model and the semi-distribution model provide an understanding that it is very important to search for how well parameters should be included in the model to describe the watershed system [6].

The development of a rainfall-runoff model using many approaches provides special attention to researchers. The developing model causes researchers need more effort in reducing the uncertainty value in the hydrological model by testing the influential factors, starting from the internal and external factors of a model. Changing the parameter value causes the discharge of the simulation results to be much different. In this case, researchers are encouraged to conduct a constitutional analysis to determine the parameters that were most influencing the results of the model, so that they become the most effective model. In other words, sensitivity analysis can help the calibration process in the model [7].

This study will combine ArcGIS as GIS software with HEC-HMS to model the hydrology. ArcGIS analyzes digital terrain information in the form of DEM (Digital Elevation Model) into the structure of river geographic data and watershed boundaries that are ready to be processed. The results of the physical characteristics of the watershed from the modelling process in ArcGIS can be entered into a hydrological modelling system for rainfall-runoff, which is HEC-HMS. HEC-HMS is very powerful and flexible software, with sufficient and accurate hydrological data, HEC HMS can run several models in it [8]. The Malino watershed in Central Sulawesi Province was chosen as the area to be studied. The output from the HEC-HMS will be compared with the unit hydrograph from each watershed.

The results of the rainfall-runoff model on the HEC-HMS display the Nash-Sutcliffe value for each rainfall-runoff model. Four rainfall-runoff models are created based on the distribution of stream order. Different treatments in each model will affect the results of the simulation model. It comes from the structure of each model that created differently. The structure of the model consists of components which are simplify the watershed conditions such as reach, sub-catchment and junctions, which each component will represent each inputted parameter value. Each model will be tested first with initial parameter values according to the available data conditions. Then the model will be tested again with several new parameters for each loss method and the transform method. Each model will produce a different hydrological response. From many variations of parameters given in the model, certain parameters will provide the greatest influence on the changes in hydrological response that occur. Thus, this study can be used as one of the guidelines in determining the parameter values to be modelled on HEC-HMS.

II. Material and Method

A. Study Area

The location of this research will be conducted in one of the sub-watersheds of the Bongka watershed, the Malino watershed, which is located in Central Sulawesi Province. The area of the Malino watershed is 124.93 km2 with the length of the main river is 19714.58 m. According to the description of the condition in Malino Watershed, the average land slope is 11.34% with elevation ranging from 16 m to 2214 m.

The condition of the watershed has a good type of land cover, where the upstream part is still covered with primary forest and its downstream is dominated by agricultural land.

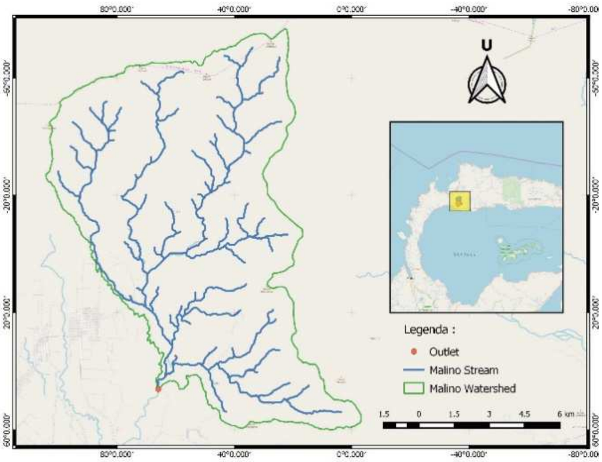
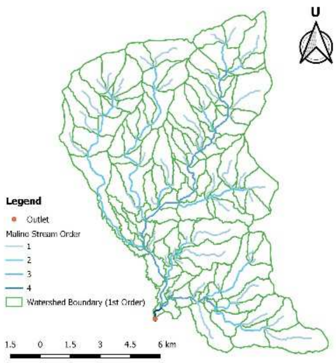
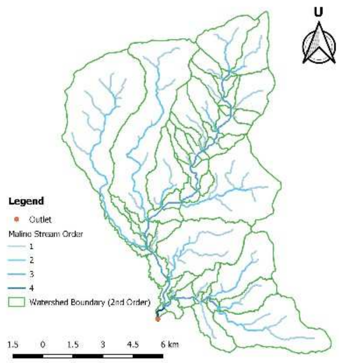


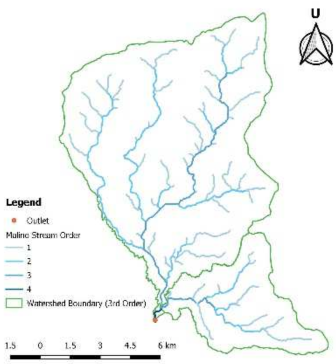
Fig. 1 Location of study area



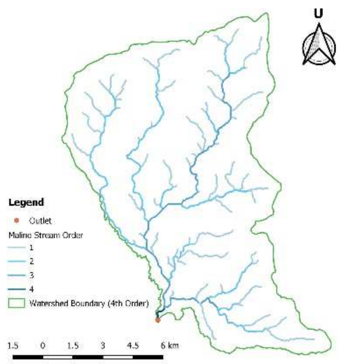
a. Sub-catchment 1st Stream Order



b. Sub-Catchment 2nd Stream Order



c. Sub-Catchment 3rd Stream Order



d. Sub-Catchment 4th Stream Order

Fig. 2 Sub-catchment based on stream order determination

Which with this land cover condition, the Malino watershed is a well-conserved watershed [9]. The Malino watershed is chosen as a research location because the conditions of the river flow path are still free and there has not been any collection for water needs, nor water structures along with the river flow.

B. Research Data

The data needed in this study come from secondary data sourced from various sources. The data that will be processed first is DEM (Digital Elevation Model). DEM used in this study was sourced from the Geospatial Information Agency or commonly referred to as DEMNAS (The National DEM). The National DEM was built from several data sources including IFSAR data (the spatial resolution: 5m), TERRASAR-X (the spatial resolution: 5m) and ALOS PALSAR (the spatial resolution: 11.25m), by adding Mass-point data from the result of stereo-plotting. The DEMNAS spatial resolution is 0.27 arcsecond, using the EGM2008 vertical datum [10].

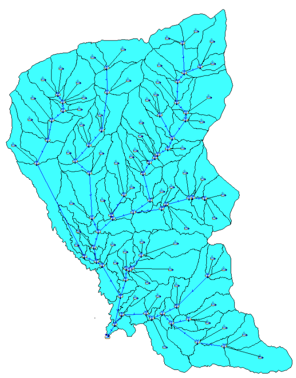
For this study, the land use data used is shapefile of Central Sulawesi province's land use in 2011 sourced from the Central Sulawesi government geoportal website. The shapefile data is cut to adjust the Malino watershed boundary. The land cover conditions in the Malino watershed consist of primary dryland forest (52.06%), secondary dryland forest (22.87%), dryland agriculture (14.02%), shrubs (11.01%) and paddy fields (0.03%). The soil data was obtained from BAPPEDA of Central Sulawesi Province in 2015. If soil is grouped by hydrological soil group, the soil conditions of the Malino watershed are classified into class C (silty-loam, 59.76%) and D (clay, 40.24%). In this condition, it can be concluded that the soil in the Malino watershed has a small loss rate.

The last data needed is the hydrology data, the most important data to create a rainfall-runoff model. The hydrological data needed include rainfall data as the input of the model and observational discharge data for calibration and comparison between the simulation model and the observation discharge. In this research, the recorded discharge from AWLR (Automatic Water Level Recorder) has been processed into the unit hydrograph of Malino watershed and is defined as a direct runoff hydrograph generated by one-unit rainfall that occurs by 1 mm of effective precipitation in one unit of time. Therefore, the precipitation data inputted for the rainfall-runoff model is 1 mm, it is done to adjust the discharge data obtained.

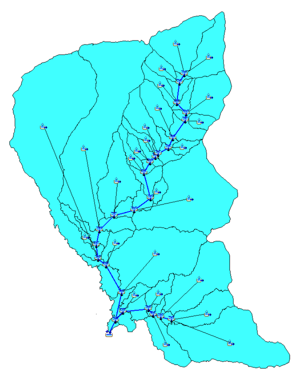
C. Research Model Tools

1) ArcGIS. The hydrological model also requires explicit specifications of spatial parameters related to geology, land use, soil, and topography. These data can be developed into a model element that can be reprocessed again hydrologically. To be able to handle both hydrological and spatial models, it needs to be combined into one integrated model [11]. Spatial modelling using GIS becomes the most important role in determining the parameters of the hydrological model with the concept of semi-distribution.

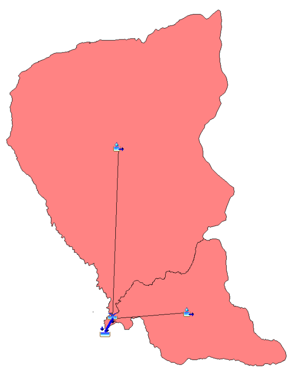
The existence of GIS in modelling spatial data for the concept of this semi-distribution model can overcome the large simplification in representing parameters at the sub-watershed scale [12]. In this study, ArcGIS software



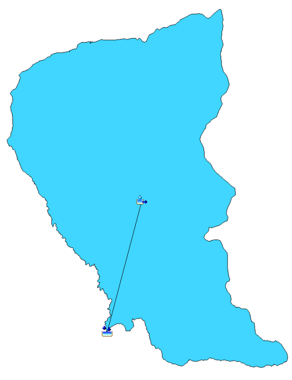
a. HEC-HMS Model for 1st Stream Order



b. HEC-HMS Model for 2nd Stream Order



c. HEC-HMS Model for 3rd Stream Order



d. HEC-HMS Model for 4th Stream Order

Fig. 3 Sub-catchment based on stream order determination version 10.3 is used in processing geospatial data. DEM data is processed with the Spatial Analyst Tool (Hydrology Tool) to delineate the watershed, show the direction of river flow, and divide the watershed into several sub-catchment. Strahler stream ordering method was used for illustrating the hierarchy of stream. The Strahler method explains that perennial stream without tributaries called first order and when two streams from the same order join together, the downstream reach increases become one order larger [13]. Then the study area will be divided into several numbers of sub-catchment based on stream order determination shown in Fig 2. The processing performed by ArcGIS will produce (1) watershed parameters in the form of watershed area and each sub-watershed area; (2)river length; (3)land slope; (4)stream slope; and (5)shape and the dimension of channel cross-section. The results of the processed data are in the form of shapefiles and attribute tables containing the values of watershed parameters.

2) HEC-HMS. In this study, HEC-HMS is used as a software that modelled the hydrological process. HEC-HMS is used for simulating the process of rainfall-runoff in the dendritic watershed system and is designed to be used in large watersheds [1]. The basin component in the HEC-HMS model is used for fulfilling the physical description of a watershed. The module contained in HEC-HMS can be used for calculating runoff volume, direct runoff, baseflow, and channel flow. Because this study focuses on surface runoff due to effective precipitation (rainfall-runoff) so that the model created will not input the baseflow parameter. HEC-HMS has various types of methods in calculating rainfall-runoff. To determine the precipitation that will occur is conducted using the loss method. This method usually calculates runoff volume by calculating the volume of water intercepted, infiltrated, stored, evaporated, or transpired and subtracted from precipitation [14]. Meanwhile, the effective runoff amount is calculated by the transform method. Direct runoff is calculated based on the excess precipitation in the watershed and converts the precipitation excess into a runoff. In this study, the SCS Curve Number method is used for calculating the loss in the watershed. The CN value parameters for this method are obtained by processing shapefile of soil data and land use data using ArcGIS software. Meanwhile, SCS Unit Hydrograph is used for calculating the transform method. This method requires value of the time lag parameter, which in the formulation there are values of flow path length, and land slope. These two parameters are obtained from processed geographic data in ArcGIS. The hydrological process does not only occur in the sub-catchment area, but the condition of flow water on the land surface also needs to be modelled in HEC-HMS. Kinematic wave is chosen to simulate surface runoff that occurs due to excess precipitation on the land surface. The parameters in the kinematic wave focus on the condition of the channel, so that the channel cross-section dimensions, channel slope, and length of the reach are obtained from DEM data processing in ArcGIS.

D. Calibration Model

A calibration model needs to be conducted to ensure that the model created has reliable simulation results. Calibration in this study was performed by comparing the results of flow simulations with the unit hydrograph data. The parameters in the model are used in proving the compatibility of the simulation results with the available unit hydrograph data. In general, HEC-HMS provides an automatic calibration tool using the Nelder-Mead method, but the results of this automatic calibration process do not provide optimal results so manual calibration was chosen for this study [15].

Calibration is conducted manually by changing each parameter value until the model get optimal simulation results. Changed parameters must be determined based on observations and measurements of watershed and flow characteristics. During the calibration process, the model performance evaluation value of the model must always be recorded to observe changes in the suitability of the model simulation results to the changed parameters.

E. Sensitivity Analysis

A hydrological model is created to simplify a complex hydrological process. The results of this simplification will not produce the most perfect simulation results, but it is hoped that the results of the hydrological model can resemble the results in observation condition [3]. Therefore, each model created needs to be understood correctly based on the method and parameters. It causes sensitivity analysis to be an important component in hydrological modelling. This analysis is used for identifying the parameters that influence the results of the simulation model. No matter how changes are made to the parameter values, it will have a large or small effect on the simulation results. Thus, it is important to know the most sensitive parameters in the model [15].

Sensitivity analysis in this study begins by simulating the model using parameters that have been optimized. The optimal parameters used are the results of the calibration process. The next step is to change the parameter values in the model. Variations in the parameters used by changing the parameters become -30% to 30% from the value with a change interval of 5%. The output to be reviewed in this analysis is the peak discharge from the simulation results, then compared and calculated to know the percentage change. The percentage change will be used to determine the elasticity ratio value (e) of each parameter. The elasticity ratio in the sensitivity analysis is used for determining the ranking of the studied parameters [16]. The parameter with the largest elasticity ratio value is the most sensitive parameter among other parameters.

III. Result and Discussions

A. Simulation Result of HEC-HMS

The final unit hydrograph results from each sub-catchment distribution can be seen in Fig. 4. The simulation results are compared with the observational unit hydrograph data. First, the model uses initial parameters in calculating SCS Unit Hydrograph for transform method, SCS Curve Number for loss method, and Kinematic Wave for channel routing. The inputted parameters are derived from data obtained by researcher. Then, the model is calibrated by doing “try and error” to optimize the parameter value. The process is conducted manually by modifying each parameter

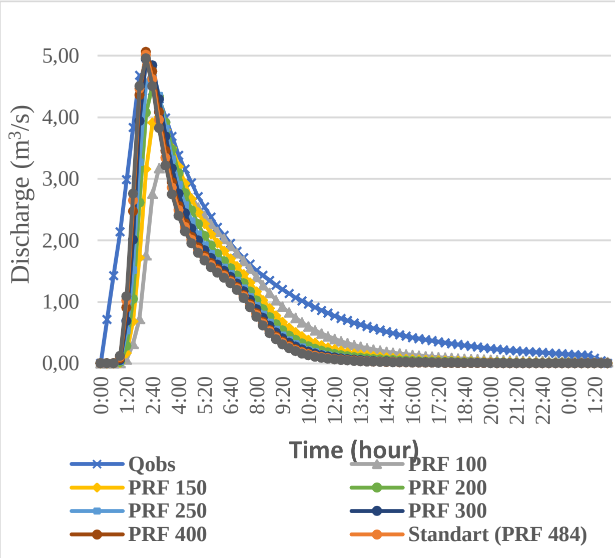


Fig. 4 Simulation Result for Various PRF Value

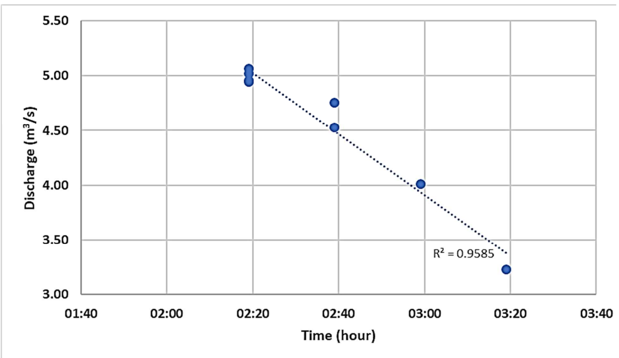


Fig. 5 Comparison of simulation result based on graph type

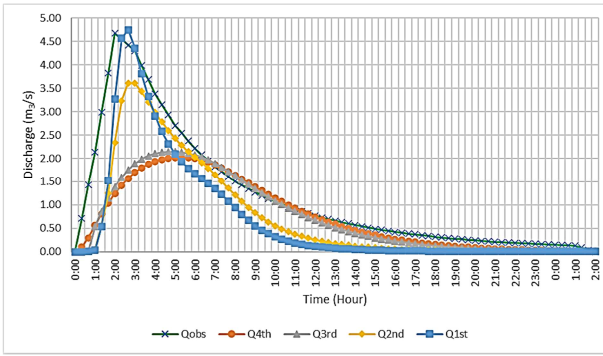


Fig. 6 Simulation Result from HEC-HMS Model

value so that it can produce compatibility between observational data and simulation results. The results obtained in the Fig. are the simulation results after the model has been calibrated.

Fig. 4 is comparison among unit hydrograph of observation, simulation of 1st, 2nd, 3rd, and 4th stream order. From Fig. 4, the simulation result each model have a different peak discharge with different time of peak. The simulation result based on first and second order distribution has simulated discharge of 4.754 m^3/s and 3.612 m^3/s at the same time to 02:40, for third order distribution has simulated discharge of 2.147 m^3/s at 04:40, and for the last forth order distribution has simulated discharge 0f 2.020 m^3/s at 05:20. The greater the value of reach order is, the smaller the resulting value of the simulation peak discharge will be. The smaller the peak discharge value is, the longer time of peak affected will be.

Based on the Fig. 4, unit hydrograph of the simulation results is different from the observation unit hydrograph. Runoff discharge that occurs before and after peak discharge tends to be different. To find out which model performance is better, it can be analyzed using the Nash-Sutcliffe test. Result from the Nash-Sutcliffe shown in Table I. From the value, all models have a satisfied result.

From that result, these values indicate that creating a rainfall-runoff model by dividing sub-catchment influences a significant difference in the simulation results. It is closely related to the parameters in the watershed and the structure of the model. In the performance of the models in Table I, it can be concluded that the greater the value of the stream order is, the better the model performance will be.

TABLE I
MODEL PERFORMANCE OF HEC-HMS MODEL BASED ON NASH-SUTCLIFFE EFFICIENCY

Model Performance	Number of Sub-catchments	NSE
1st Stream Order	120	0.718
2nd Stream Order	51	0.713
3rd Stream Order	3	0.511
4th Stream Order	1	0.462

B. Comparison of The Simulation Result Based on Graph Type

It has been mentioned earlier that the shape of the simulation unit hydrograph is different from the observation hydrograph unit. Conditions that cause the shape of the graph of the simulation results are not suitable influenced using factors used in direct runoff analysis (Transform Method). In the SCS Unit Hydrograph method, it defines curvilinear in the unit hydrograph by first adjusting the runoff percentage that occurs before the peak discharge occurs. In this method, a standard unit hydrograph is formed based on 37.5% of runoff discharges that occur before the peak discharges. This standard hydrograph unit has a PRF (Peak Rate Factor) value equal to 484 [17]. The PRF value certainly influences the shape of the simulation results hydrograph. In addition, the PRF value can be determined based on the topographic conditions of the watershed. To obtain the appropriate results for Malino watershed, it will try to simulate first order model with different PRF values, the simulation result can be seen in Fig. 5. Then, the simulation result will be compared by plotting the values of Q_p and t_p each model on a graph and calculating the correlation value between that two values. The graph can be seen in Fig. 6. This process is performed to determine the effect of various PRF value on simulation results.

From the graph above, the R^2 value for simulation result using various type of PRF value for transform method is 0.9585. These results are based on the plotting between peak discharge and time of peak from simulation result. The R^2 value in Fig. 6 shows that the change of the PRF value on the SCS Unit Hydrograph has a large influence on the simulation result linearly. Based on various simulation results, the PRF 250 was chosen to be used in the Malino watershed model. This value is chosen based on the results of the peak discharge values that are the closest to the observation peak discharge.

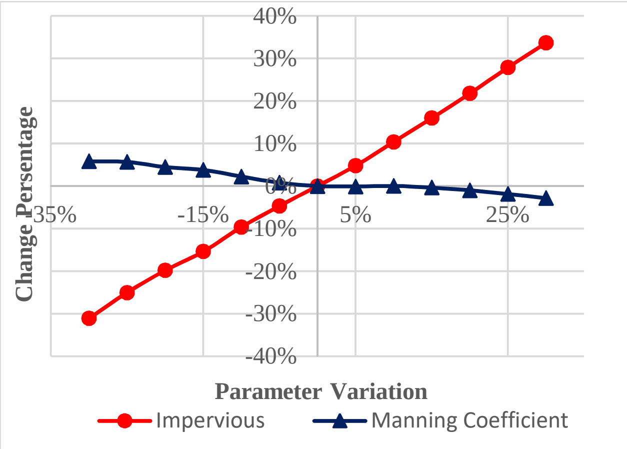


Fig. 7 Sensitivity analysis graph for the variation of each parameter

TABLE II
ELASTICITY RATIO

Rank	Parameter	Elasticity Ratio Value
1	Impervious	1.0794
2	Curve Number	0.1441

C. *Sensitivity Analysis*

Sensitivity analysis is performed on the parameters that used for the SCS Unit Hydrograph and SCS Curve Number. The sensitivity analysis in this study is used for evaluating the event model. There are four parameters analyzed for sensitivity, these parameters include the curve number, impervious, lag time, and manning coefficient. One of these parameters will be analyzed by changing the parameter values to vary with a range of -30% to 30% and the interval used is 5%, while the other parameters are fixed at a constant. The sensitivity analysis graph and Elasticity Ratio value for each parameter can be seen in Fig. 7 and Table II.

From the results of the above table, from the two studied parameters, impervious is the most influential parameter and sensitive to the parameter changes made. When compared with the manning coefficient, the impervious has a higher level of sensitivity. Changing the impervious parameter will increase the peak discharge value when the parameter value gets bigger. Meanwhile, changing the manning coefficient parameter to the smaller value will cause the peak flow of the simulated results greater.

IV. CONCLUSIONS

Based on the analysis and discussion above, several conclusions can be summarized as follow: In this study, the sub-catchment distribution for the rainfall-runoff modelling has a significant influence on the simulation results. It is caused by the structure of the model formed based on the division of stream order. In this study, the most optimal results are produced in models with sub-catchment distribution based on the first order. It can be concluded that the greater the number of sub-catchment distributions performed is, the batter the performance models will be produced. From the comparison of simulation results for various types of graphs on the SCS Unit Hydrograph method, it can be concluded that based on the R^2 value, the determination of the PRF is very influential on the simulation results of the model. PRF 250 was chosen used in the Malino watershed model. This value is chosen based on the results of the peak discharge values that are the closest to the observation peak discharge. From the results of the sensitivity analysis conducted on the selected parameters, it was concluded that the impervious is the most sensitive parameter. Hence, in rainfall-runoff modelling, small changes in the impervious parameter can have a large effect on the simulation results. These parameters are also the most parameter that can be used to calibrate manually.

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