An Advanced Empirical NRCS-CN Model Estimation for Ungauged Catchment Insufficient Data

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Abstract— The calculation of runoff is continuously considered a difficult analysis to define specific prediction methods in ungauged catchments. This leads to the implementation of an observed model to determine curve number (CN) and estimate peak discharge from ungauged basins. Therefore, this study aimed to modify an experimental NRCS model through fieldwork and conduct sensitivity analysis for relevant modeling procedures. In the analysis, the assessment of CN required land use, soil, infiltration in situ measurement, and Hydrological Soil Group (HSG) parameters for the catchment area. The determination of infiltration rate was also initially carried out using the Horton method (double-ring infiltrometer), accompanied by the evaluation of CN through soil classes and land use parameters. Based on infiltration rate and soil classification, HSG was significantly defined for the catchment area. The results showed that the analytical parameters in rainfall-runoff modeling included the Composite Curve Number (SCS-CN (I_a /S) with a ratio value of 0.2. This was accompanied by the potential retention maximum (S) of 264.37 mm, with the initial proportional abstraction (I_a) being 52.87 at an assumed preliminary coefficient of 0.2. Therefore, the CN composite estimation was 65.5, and the correlation between P and Q was evaluated using graph analysis. The trial CN ranging from 39-74 were also significantly considered to optimize the development models of HEC HMS for the best performance, proving that the improvement of CN was interrelated with discharge.

Keywords— Curve number; land-use; NRCS-CN; peak discharge; fieldwork.

I. INTRODUCTION

The analysis of ungauged catchments is presently considered due to inadequate data, with meteorological modeling providing an alternative solution. This catchment analysis shows that the runoff calculation remains difficult when defining specific prediction methods. "In the 1950s, the curve number (CN) model was developed under the leadership of the United States Department of Agriculture (USDA) Soil Conservation Service to empirically represent the average relationship between P and Q, as shown in Fig 1 [1].
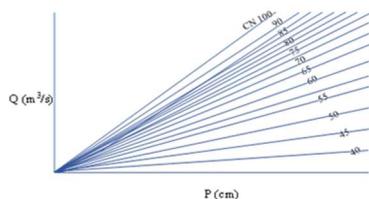

Fig. 1 Conventional CN model

Based on the standard conventional CN method, the coefficient initial loss is 0.2, considering the differences between λ = 0.2 and λ = 0.05 [1]. This shows that the rational and NRCS models can estimate the surface runoff depth in each micro sub-basin [2]. The models are also implemented as observed methods for estimating peak discharge from an ungauged basin [3,4]. Moreover, CN is an indicator obtained by the Soil Conservation Service commonly presenting direct runoff through drainage areas [5]. This indicator is often determined using empirical runoff models with a specific contour in a small-area catchment [6]. CN is also analyzed using two substances from the standard or approximated NRCS tables through rainfall intensity measurements and discharge data analysis [7]. The standard conventional CN method subsequently assumes initial loss (I_a) with a specific maximum retention potential (S, mm) [8], proving that "rainfall-runoff process affects watershed components, including segment, distance across, section, profile, drainage model, soil class and vegetation coverage, land usage, and hydrological conditions" [8]. This method is presently

selected due to the frequent implementation of runoff assessment, using various methods such as soil permeability, land use, and antecedent moisture conditions, which have been significantly implemented for river basin analysis [8]. Peak discharge is also determined by spatial-temporal distribution, precipitation, Tc, and CN to define catchment characteristics and sink achievement [9]. In the discharge determination, Tc is considered the time of concentration used by the water to reach the sink, with the determination of CN for a watershed requiring land use, soil, and moisture condition parameters. Furthermore, soil data are commonly obtained from the local NRCS or stated in hardcopy surveys [9]. In this context, the surveys prioritize soil categorization through specific physical characteristics, with CN estimation requiring relevant land cover mapping. The manual calculation of CN is also complicated and time-consuming for large areas or drainage basins, prioritizing the appropriate analytical significance of mapping through a Geographic information system [9]. However, the model estimates the amount of runoff depending on land usage and soil class [10].

Direct runoff is the sum of rainfall quantity, with precipitation and duration affecting the main ratios between the potential and actual discharge volume. This runoff model is equivalent to the ratio between the maximum retention potential and infiltration volume, leading to a simplified mass in the equilibrium equations. Based on a previous report, "the model established a design tool in the 1950s, under the leadership of the United States Department of Agriculture SCS" [11]. "The tool empirically prioritized the average relationship between storm event rainfall (P) and the corresponding runoff (Q), with the rate of infiltration data applied in Hydrological Soil Group (HSG) to define CN" [11]. "Quite a few types of HSG were also observed, namely A, B, C, and D, with definitions stated in HSG Characteristics" [11]. Moreover, the original equation formulation of the CN method is SCS-CN. I_a/S, with I_a of 0.2 [11,12]. This modified SCS-CN model used independent equations through five antecedent rainy days to estimate the existing moisture [13,14]. "Surface runoff is the direct discharge caused by rainfall immediately flowing at land cover after a storm" [15]. The runoff process is subsequently significant in calculating adequate rainfall and separating infiltrated soil water from the moisture incorporated on the network surface [16]. This process depends on several factors: rainfall intensity, soil absorption capacity, topography, and plant type [16]. Event-based runoff coefficients are also initial parameters obtained from time series data, providing preliminary information about the cumulative rainfall drainage of catchment areas [16]. In addition, the CN model is developed by US-SCS hydrologists, identifying direct surface runoff in ungauged agricultural and non-agricultural watersheds [17,18]. This proves that the ratio of peak surface flow to the rain intensity is C-Coefficient [19], with relevant runoff values modifying the outcomes of flood discharge calculations [20]. The accurate calculation of CN is also commonly conducted by analyzing and evaluating hydrological experience" [21]. "SCS-CN Method is subsequently implemented for rainfall-runoff modeling [21], where the curved section of the river is highly influenced during frequent channel shifting" [22]. Therefore, this study aims to modify an experimental NRCS model through fieldwork and conduct sensitivity analysis for relevant modeling procedures.

II. Materials and Method

An observed NRCS model was modified through fieldwork, accompanied by determining peak flow in ungauged catchments. This analysis was significant because peak flow was determined using field evaluation and compared to a relevant rational method through the basic CN model. Moreover, the model was implemented as an essential parameter assessment in HEC HMS modeling. "CN was also the significant parameter model for simulating and predicting rainfall-runoff modeling" [23].

A. Study Area

The implemented catchment area was at Lanang River Basin, Kediri, East Java, Indonesia, where the two areas selected were the Districts of Ngadirejo (downstream) and Pandantoyo (upstream). These areas' sampling distances were approximately 20 Km, with Google Maps used to determine the river flow direction and ArcGIS. The river's lengths and the catchment area and width were also 40.083 Km, 91.526 Km, and 2.283 Km, respectively. Based on the overlayed GIS data of land use maps, the settlements/villages, paddy fields, and industrial plantation forests in Lanang River Basin were located at 32%, 28%, and 11%, respectively. The comprehensive details of the study area and land-use surface cover in Lanang River Basin, Kediri, East Java, Indonesia, are presented in Figure 2.
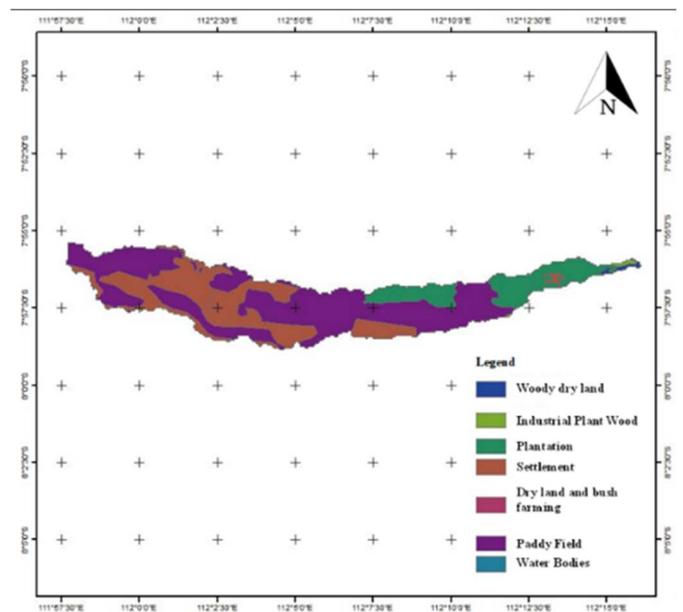

Fig. 2 Study Area and Land Use in Lanang River Basin, Kediri, East Java, Indonesia

B. NRCS-Model

Since dryland farms and forests were the most extensive land use elements in the Lanang River Basin, the "SCS-CN method was subsequently defined using the following equations" [24]. In these equations, each combination of the slope class, soil type, and land use parameters was integrated into a runoff attribute to adopt a rational approach" [25].

$$Q = \frac{(R-I_a)^2}{R-I_a+S} = \frac{(R-0.2S)^2}{R+0.8S} \quad (1)$$

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (2)$$

$$CN = \frac{25400}{S+254} \quad (3)$$

where, Q is direct runoff discharge, R is rainfall, I_a is initial loss, S comprises retention capacity maximum, and CN is curve number. The final NCRS-CN model equation is subsequently expressed as follows [25]:

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \; if \; P > I_a \quad (4)$$

$$I_a = \lambda S \quad (5)$$

where, λ = coefficients of Initial loss and S = retention capacity maximum. SCS-CN was also analyzed using the Evaluation of Direct Runoff, using the Mishra and Singh (MS) model. This analysis was significantly carried out to estimate existing moisture through the separate equations prioritizing five antecedent rain days, precisely Equation (5).

C. HSG Classification

HSG classification for the Lanang River catchment was also similar to CN values in the mapping. However, the overlays of HSG and land-use mapping units were considered in Table 1 [26].

TABLE I
HSG CLASSIFYING LANANG RIVER CATCHMENT AREA

Land use land cover	symbol	USDA14_2	Soil class	CN	Area (km²)
Wooded area	Hs	Vitrandic Eutrudepts	A	49	0.495575
Forestry	Ht	Vitrandic Eutrudepts	A	49	0.319214
Plantation	Pk	Oxyaquic Eutrudepts	A	67	0.036783
Plantation	Pk	Arenic Eutrudepts	A	67	8.221665
Plantation	Pk	Vitrandic Eutrudepts	A	67	1.344865
Residence	Pm	Oxyaquic Eutrudepts	A	57	5.089586
Residence	Pm	Arenic Eutrudepts	A	57	0.469811
Residence	Pm	Aquic Eutrudepts	A	57	6.121364
Dry fields	Pt	Oxyaquic Eutrudepts	A	67	0.000811
Bushes and dry fields	Pc	Arenic Eutrudepts	A	67	0.001829
Fields	Sw	Oxyaquic Eutrudepts	A	67	14.408766
Fields	Sw	Arenic Eutrudepts	A	67	21.352856
Fields	Sw	Aquic Eutrudepts	A	67	33.060863
Fields	Sw	Vitrandic Eutrudepts	A	67	0.007776
Fields	Sw	Vitrandic Eutrudepts	A	67	0.007223

III. RESULTS AND DISCUSSION

Based on the results, the estimated CN parameter was considered the correlation (S) using Equation (5). The following calculation is significantly performed to determine the potential retention maximum.

$$S = \frac{25400}{CN} - 254 = \frac{25400}{49} - 254 = 264.37 \; mm$$

where, S, P, and Q are presented in millimeters. Based on Equation (6), the calculation of the preliminary reduction prioritized the evaluation of Initial Loss Coefficient through NCRS Method recommended for broad implementation. In this evaluation, $\lambda = 0.2$ was used due to being highly implemented for the original calculation of I_a in relevant previous reports, as presented in the following equation.

$$I_a = \lambda S = 0.2 * 264.37 \; mm = 52.87 \; mm$$

Initial Loss, Potential Retention Maximum, and CN computations were applied in HEC HMS simulation to transform precipitation into the outflow [27]. This application led to the evaluation of various vital areas, where the HSG of the basin was estimated as Type A, according to ArcGIS mapping and infiltration rate at the upstream and downstream regions [28]. The parameters of rainfall intensity, runoff coefficients, and catchment areas were essential to calculate peak flow in rational method processes [29]. Therefore, the calculation of Initial Abstraction, Potential Retention Maximum, and CN were applied in HEC HMS simulation to transform precipitation into the outflow [30]. The assessment of vital areas also prioritized ArcGIS mapping and infiltration rate, where the HSG of the basin was estimated as Type A [30]. The rational method was subsequently analyzed to calculate peak flow for rainfall intensity, runoff coefficients, and catchment areas [31]. Table 2 significantly shows the comprehensive description of CN analysis.

TABLE II
CN DATA ANALYSIS BASED ON HSG STANDARDS AND FIELDWORK IN HEC HMS

CN	S	λ	I_a	Land use land cover
39	397.2	0.2	79.46	Crops-Forage good hydrology condition
49	264.3	0.2	52.87	Farm
58	183.9	0.2	36.79	Crops-Forage fair hydrology condition
60	169.3	0.2	33.87	Farm
65.5	133.7	0.2	26.76	Residence

Source: data analysis, 2022

Based on the results, "the river flow prediction was a major hydrological challenge in ungauged catchment areas, such as watersheds without observed discharge" [32]. This challenge led to the implementation of Sensitivity Analysis (SA), a primary hydrological tool commonly used to identify influential parameters and provide a perspective on the relationship between systematic model processes [33]. The validity of the CN model was also determined through field observations and the functional representation of the rainfall-runoff relationship [34]. Furthermore, the HEC HMS Hydrological model was used to develop a relationship between rainfall-runoff and CN for the subsequent analytical development in the study area [35]. This proved that an optimization scenario prioritizing two distinct parameters with varying values was assessed and evaluated. The calibration of the analyzed model also focused on implementing scenarios for a single sub-basin and multiple basins (5 sub-basins). Another common profile was subsequently considered for validation, namely the Lamong

watershed, considered an ungauged catchment in the Lanang facility. In addition, the calibration process ensured the simulated model was closely supported by reality, with the UTM 49 Southern WGS 84 coordinate system implemented for the basin manager. The results showed the values of CN, Coefficient Initial Loss (λ), as well as the Computed and Observed Flow at 43, 0.1, 0.3 m3/s, and 0.1 m3/s, respectively. The implementation of simulation also remained necessary for the achievement of field outcomes. According to the simulation of one sub-basin time series between rain and Ngadirejo AWLR data (1536 observation data), hourly observations were not close to the field outcomes. In the Pandantoyo AWLR watershed, optimization 1 was also carried out with Initial CN, Minimum, and Maximum Values at 65.56, 43, and 99, respectively. Fig 4 shows the simulation of one sub-basin outflow and observed flow, using HEC HMS 4.11 application.

The simulation outcomes of one sub-basin time series were observed between rain and Ngadirejo AWLR data, proving that the sensitivity analysis for the previous section was applied to Lanang watershed, using 2010-2022 precipitation information. CN Initial Value also ranged from 43 to 58, affecting the preliminary loss and direct runoff [35]. Therefore, the HEC HMS model was implemented to replicate the loss and runoff, with no baseflow assumed due to the selection of precipitation flood models [35]. Specified Hyetograph and Loss method was subsequently implemented, prioritizing the SCS CN model for observed and computed flow. CN value was also determined in the infiltration rate analysis, prioritizing a function of soil type, antecedent moisture condition, and an essential hydrological predictor of direct runoff or penetration from excess rain [35].

Fig. 3 The graph results simulating one sub-basin outflow and observed flow development from HEC HMS 4.11
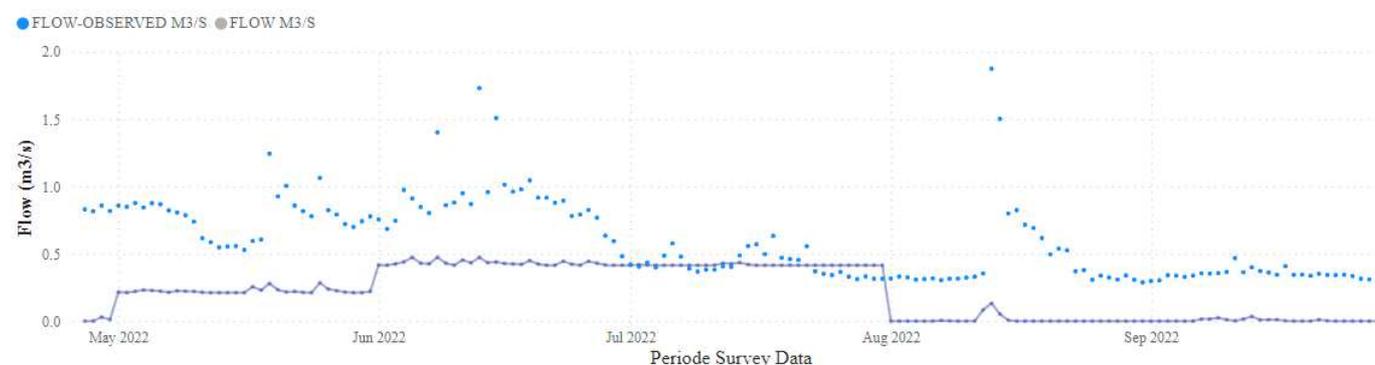

Fig. 4 Graph results simulating one sub-basin outflow and observed flow development from HEC HMS 4.11 in downstream CN 53-55

Based on Fig 5, a relationship was observed between peak discharge and the value of CN, proving that a more significant flow coefficient caused an increased CN estimate. Fig 5 also showed that the correlation between CN and peak discharge was significantly determined. The value of Peak Discharge was subsequently affected by CN, Initial Loss Coefficient, and Lag time. These parameters were highly significant due to effectively influencing the components of peak flow, such as solid area, soil classification, and rainfall. Therefore, greater discharge values significantly led to increased flow coefficients. This was in line with Fig 6, where a relationship was found between peak discharge and flow coefficient. Sensitivity analysis was also conducted for the simulation in HEC HMS 4.11, using Lag Time and Initial Loss to evaluate relevant impacts through a specific CN value of 49.

The overall analysis of this study found that the curve number correlated with the runoff coefficient. The definition of a curve number can also be referred to as a runoff curve number [36], and a curve number (CN) is the most widely preferred model for predicting rainfall that becomes runoff. A global model where many literature studies are supportive and well documented so that it can become an essential standard for determining runoff with the characteristics of watersheds such as land use/cover (LULC), soil type, Hydrologic soil group (HSGs), and antecedent soil moisture condition (AMC) [12,13,37]. In this study, a sensitivity analysis of the rainfall-runoff model was carried out based on the selection of parameters in trial optimization based on [38] and to simplify the iteration of the modeling process with sensitivity analysis. The AWLL Pandantoyo watershed was optimized with the

parameters SCS Curve Number-Curve Number and SCS Curve Number – Initial abstraction λ = 0.2 with a range of CN 49-55. The relationship between curve number, peak flow, and Initial abstraction on the estimated maximum storage retention potential. This value is related to the sensitivity analysis of the use of curve numbers in modeling, as shown in Fig 5.
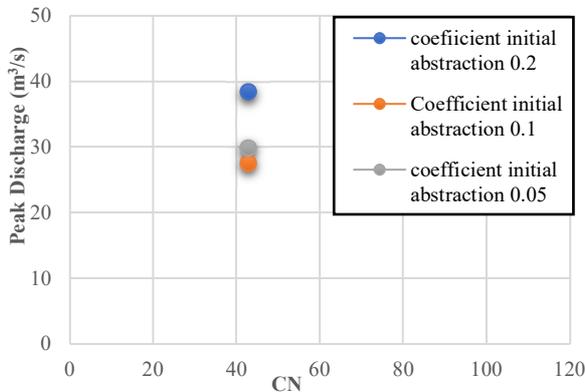

Fig. 5 CN 49 correlation with Peak Discharge simulation results using HEC HMS 4.10
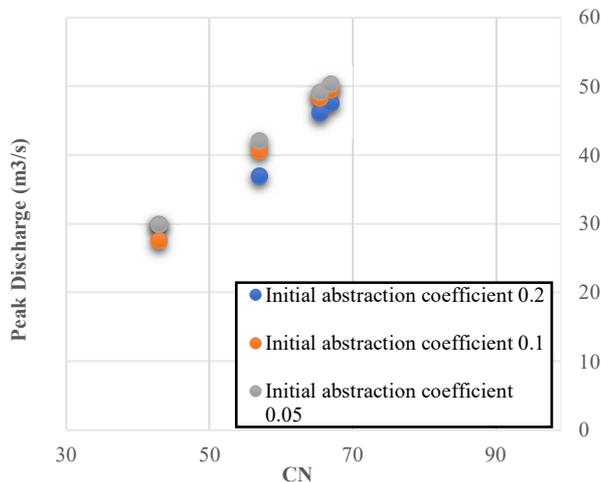

Fig. 6 CN correlation with Peak Discharge simulation results using HEC HMS 4.10

Nash-Sutcliffe Efficiency (NSE) was determined by using Equation (1) to evaluate peak flow denoted by PNSE, with a value of 1 considered a perfect fit (Nash and Sutcliffe, 1970). Values between 0.0 and 1.0 were also commonly portrayed as acceptable performance levels, with NSE > 0.50 being satisfactory, as shown in Table 3.

TABLE III
AWLR NGADIREJO CALIBRATION SIMULATION USING CN OF 53-55

Optimization	Computed	Observed
Peak discharge	0,5 m³/s	1,1 m³/s
Discharge volume	19,72 m³	18,93 m3
RMSE Std Dev	1,2	
Nash Sutcliffe	-0,384	
Percent Bias	3.30%	

Time lag (T_L) and time of concentration (T_C) define how quickly a stream responds to precipitation to generate runoff.

TABLE IV
LAG TIME DATA FOR SIMULATION

Method	Lag time hours	Lag time (min)
Kirpich	8,8032	528
Snyder	7,470	448
SCS	1,081	64,8

TABLE V
PEAK DISCHARGE HMS HEC SIMULATION USING LAG TIME FOR ONE SUB-BASIN AND AWLL MEASUREMENT IN UPSTREAM (PANDANTOYO VILLAGE)

Lag time (min)	Impervious area (%)	CN	Initial Abstraction (mm)	Method Estimation Time of concentration
17.5	0.1	49	52.87	Stream Velocity by Manning Equation, t channel
64.8	0.1	49	52.87	SCS
448	0.1	49	52.87	Snyder
528	0.1	49	52.87	Kirpich

Some essential points associated with Type Rainfall-runoff Models are as follows:

1) Conceptual Models: Models that use simplified representations of hydrological processes, such as the Soil Conservation Service Curve Number (SCS-CN) model and the Storm Water Management model (SWMM).

2) "Empirical Models: Models based on observed data and statistical relationships. Adaptive Neuro-Fuzzy Inference System (ANFIS), Artificial Neural Network (ANN), dan Support Vector Machine (SVM)"[39]

3) Physical Process-Based Models: Hydrological simulation using physical laws (HBV) model and Soil and Water Assessment Tool (SWAT)

This study was combined with conceptual models and empirical models.

Peak Flow determination using the rational method, usually for watershed area < 500 km². We need spatial data to determine watershed characteristics. Applying GIS and remote sensing techniques obtains land cover and soil data to find CN values for modeling to predict peak runoff. The SCS curve number loss method integrates with the HEC-HMS model, which is used for runoff estimation to achieve accurate results given the limitations of available data [40]. Catchment characteristics depend on land use, soil quality, or appropriate soil classification, and determining the curve number will also be closely related to land coverage and moisture conditions [41]. Determining specific CN values in modeling is based on the handbook. From the optimization results, the CN value used for optimization in the Lanang watershed with the Pandantoyo AWLL calibration will give different results from the Ngadirejo AWLL calibration due to differences in catchment characteristics in the study area. Modeling with a curve number range of 49 – 55 will produce a model with nearly actual field conditions. Meanwhile, for Ngadirejo, the modeling considers actual conditions in the field in the curve number range 53-55. This curve number value differs between upstream and downstream, which is influenced by land coverage. The difference in land coverage also affects the value of selecting the curve number.

IV. Conclusion

In conclusion, the basic models for determining CN were developed through field analysis and the rational method of measuring peak discharge. The improvement in infiltration rate influenced CN values, leading to a composite and maximum rainfall-runoff coefficient of 65.5 and 0.4 in 2022, respectively. CN parameter correlated with the Potential Retention Maximum (S) and Initial Proportional Abstraction (I_a) at 133.78 mm and 52.87, respectively. Meanwhile, the sensitivity analysis used CN = 49, providing S = 264.37, Impervious area = 0.87%, and Lag time = 17.5 mins. Different parameters should be used to achieve optimum modeling performance in future analyses. Establishing a reference or standard for CN determination was necessary for several soil types regarding the existing conditions or land use in tropical countries such as Indonesia. Therefore, a standard or reference prioritizing soil type and existing conditions was needed to ensure accurate hydrological cycle assessment in the affected areas.

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