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Creating a Rainfall-Runoff Model for Measuring Streamflow from First-Order and Ungauged Headwaters of the Tropically Medium-Sized Watersheds in Northern Thailand

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Abstract

This study investigated the suitable Initial abstraction ratio (λ) for estimating the depth of runoff in northern Thailand. The Initial abstraction ratio (λ) and curve number (CN) are two catchment parameters in the Natural Resources Conservation Service-Curve Number method (NRCS-CN). In addition, the λ is considered a regional parameter, therefore, a rainfall-runoff model for estimating streamflow in first-order and ungauged headwater of the tropically medium-sized watersheds in northern Thailand should be created to gain the more accurate runoff for this particular region. NRCS-CN was employed to determine the λ in five watersheds, evaluating the performance of the modified λ values and determining the correlation for potential maximum retention ($S_{0.2}$) from the original Curve Number (CN) equation with the revised S_λ value. A set of instruments comprised a rain gauge and a water stage recorder installed at each watershed. The initial abstraction (I_a), λ and CN of 80 storm events in 2018 and the S_λ-$S_{0.20}$ correlation equation were calculated. The runoff model assessment from 72 selected events in 2019 was validated. The results revealed a median λ of 0.045. The runoff model assessment used the data from the measuring station compared to those calculated from the created rainfall-runoff model provided more accurate runoff and better responded to Nash-Sutcliff coefficient (NSE), coefficient of determination (R^2) and percent of bias ($PBIAS$) (0.92, 0.92 and 1.91 respectively). Regarding the Watershed-Specific S correlation equation based on the S correlation equation between $S_{0.045}$ and $S_{0.20}$ values, R^2 was 0.97. It is recommended that the created model with the λ of 0.045 should be used for future simulations in the 100 to 250 km² tropically medium-sized watershed.

Keywords: First-order-stream watershed; Initial abstraction ratio; NRCS-CN method; SCS-CN method; Ungauged watershed

1. Introduction

Countries in Southeast Asia, including Thailand, are in the tropical zone where rain and climate fully support the function of watershed structures, especially at headwaters or the smallest streams at the stream origin. The headwaters usually have a good stream condition such as well geomorphology, and suitable streambed particle sizes and current velocity. They also have riparian vegetation, canopy cover, woody debris, pool, algal biomass, riffles and invertebrate diversity. Therefore, the headwaters can respond to their function correctly. The headwater function comprises supplying water to the basin, storing, transforming and transporting organic matter and nutrients, storing and transporting sediment, and buffering water temperature. From the headwaters' effective structures and functions, rainwater can be retained and gradually released into streams. As a result, a hydrograph has a long duration, i.e., a long time to peak with low peak flow. Moreover, it has low vulnerabilities to flash flooding and landslide.

In the previous decades, Thailand is facing invasions and deforestation problems in the headwaters, especially in the Nan river basin, affecting the watershed structures and functions. The retention capacity of a watershed is reducing by comparing the observed hydrograph from runoff measuring stations in several uncontrolled catchments. Hydrograph features a shorter duration and time to peak and has a high peak flow due to lower lag times. These problems are making more vulnerable to flash flooding and landslides.

In order to prevent and mitigate the damage resulting from flash flooding and landslides in downstream areas, headwater management is required and it is necessary to know the volume and timing of streamflow and the characteristics of hydrograph from measuring stations.

Headwater management involves a complex array of measurements of volume, timing of the flow, water quality within the river basins and more. Characteristics of resources within watersheds such as land cover, soil properties, rainfall-runoff of natural resources and particularly the volume of rainfall and runoff must also be accurately and efficiently measured and analyzed. All of these are possible where large-scale upstream resource management operations exist. However, the headwaters of Thailand are mostly small streams without tributaries or first-order streams, with watershed areas between 100 to 1,000 sq.km or medium-sized (Singh, 1995), and have had no measuring stations to collect rainfall and runoff data or ungauged watersheds.

Considering the characteristics of Thailand's upstream areas and the limitations of their management, it is necessary to estimate the value of rainfall-runoff by using a mathematical model.

In recent years, many countries worldwide commonly used hydrologic models to estimate direct runoff from storm rainfall in uncontrolled watersheds and to analyze the watershed response to the changes stimulus by human activities. These models all have different complexities. The key limitations of these models are related to their intensive input data, a large number of parameters and calibration requirements. Suitable features of a model should be simplicity and accessibility with few data requirements and clearly stated assumptions (Shi *et al.,* 2009).

The NRCS-CN method developed by the USDA-Natural Resources Conservation Service or NRCS (formerly USDA-Soil Conservation Service or SCS) (SCS, 1985) is the most popular method worldwide and even in Thailand. Several Thai government agencies have used this method in the study of direct runoff from storm rainfall. This method is an empirical model that is used to estimate the depth of runoff from a given depth of rainfall with two catchment parameters such as curve number (CN) and initial abstraction ratio (λ). It is implemented within hydrological models such as the Soil and Water Assessment Tool Model (SWAT model), Storm Water Management Model (SWMM).

Even though there are several ways to estimate *CN* from field survey data, the median *CN* estimate of the storm, according to NEH-4 (National Engineering Handbook Section 4: Hydrology), is the most widely used method worldwide including in Thailand as mentioned earlier. This method can be used with both "ordered" and "natural" datasets. For large storm event consideration, the Low *P*-High *CN* bias must be carefully considered. The median or mean *CN* value that is appropriate for the application must be a value that does not cause bias in the dataset. But if the analysis contains few samples, the median *CN* is more appropriate as the use of median *CN* can reduce the impact of outlier data (Schneider and McCuen, 2005).

NEH-4 has performed an example of determining the representative *CN* of a watershed by dividing the P-*Q* curve into two equal parts to find the median *CN*. This *CN* values is representative of AMC-II conditions and are considered representative *CN* value of the watershed. This *CN* value is known as *CN-II* (SCS, 1985; Hjelmfelt, 1991; Mishra *et al.,* 2007).

Regarding estimating λ value, NRCS offers a tradition λ value of 0.20 for calculation; however, many studies have shown that in order to predict the amount of runoff, the λ value which is less than 0.20 is more predictable than the tradition λ value. Since the λ value is considered a regional parameter, it should be analyzed from the data in the study area. For example, Woodward *et al.* (2003) analyzed the median λ based on data gained from 307 watersheds covering 23 states of the United States and suggested a rounded value of λ which was equal to 0.05. Mishra *et al.* (2004) conducted research on rainfall-runoff data collected from 234 small and large river basins in the United States and the median *CN* corresponding to the AMC-II method of NEH-4. The findings revealed λvalues were between 0.001 to 0.390 and the mean was equal to 0.095. Yuan *et al.* (2014) examined optimal λ from eleven watersheds in south-eastern Arizona in the United States with semiarid watersheds and found out optimal values for λ ranged from 0.01 to 0.53 due to different watershed characteristics. D'Asaro and Grillone (2012) discovered the appropriate λ value for the Mediterranean Area from their study on 61 river basins in the Sicilian watershed. The findings showed the median λ was 0 for natural data and 0.05 for ordered data. Currently, Ling *et al.* (2020) reported a λ value of 0.05 exploited in a research study carried out by a research team at the Wangjiaqiao watershed in China.

Therefore, the main objective of the study was to create a rainfall-runoff model for measuring streamflow from first-order and ungauged headwaters of the tropically medium-sized watersheds in northern Thailand. The five headwaters in the Nan river basin which are first-order streams and medium-sized watersheds, namely Ngaen Watershed, Kon Watershed, Khwang Watershed, Sao Watershed and Pua Watershed were selected. The three sub-objectives of the study were: (1) to determine the initial abstraction ratio (λ) in five experimental watersheds in the northern part of Thailand by analyzing measured rainfall-runoff events, (2) to evaluate the performance of the modified λ values with observed rainfall-runoff data, and (3) to determine the correlation for potential maximum retention ($S_{0.2}$) obtained from the original Curve Number (CN) equation with the revised potential maximum retention (S) value obtained from the model calibration from rainfall-runoff data gained from the five watersheds of the study area.

2. Materials and Methods

2.1 Study area

The Nan River Basin is located in the northern part of Thailand. It lies along the north-south bearing of the Nan River, the main river of the basin. The Nan River originates from the Luang Prabang Mountains, flowing through the plain between the valleys before running down to the Sirikit Dam Reservoir. Therefore, the upper Nan River Basin is the above part of the Sirikit Reservoir. It thus plays an important role in providing water flowing into the reservoir. Guidelines for selecting the study areas were based on the physical characteristics of the river sub-basin such as watershed area, slope, length of slope, length of river basin, altitude, land use and soil properties, etc. The guidelines also included a sub-river basin that was an upstream watershed in the region of the Nan River Basin above the Sirikit Reservoir and which was an early branch of the river before flowing down to combine with the Nan River, the main river.

The selected first-order-stream watershed, which was a study area, was located in the Upper Nan River Basin. It consisted of five watersheds, namely the Ngaen, Kon, Khwang, Sao and Pua Watersheds. They all originated from the upstream creek of the watershed that flows together with the Nan River. It was located at latitude 18º 36' 5.09" N and 19º 38' 4.55" N to 100º 35' 6.85" E and 101º 6' 30.85" E. Watersheds in the study are shown in Figure 1.

According to land use and soil group maps in 2016 from the Land Development Department, land use of the watersheds was 44.06% deciduous forest, followed by 17.31% crop rotation and 9.80% farm plants. In this study, soil characteristics of 70.21% of the total basin areas where a topographical slope of more than 35% is a conservation area denote as a slope complex (SC). Most of these areas still have not observed soil properties. Therefore, this research had randomly verified soil properties at two locations in each watershed. The physical characteristics of the watershed areas were analyzed by a spatial resolution of 30 m or 30 m-DEM (Digital Elevation Model). It was found that the study area was 105.72-233.87 km². The length of the main channel was between 18.41-37.21 km and streams had a trellis drainage pattern as shown in Table 1.

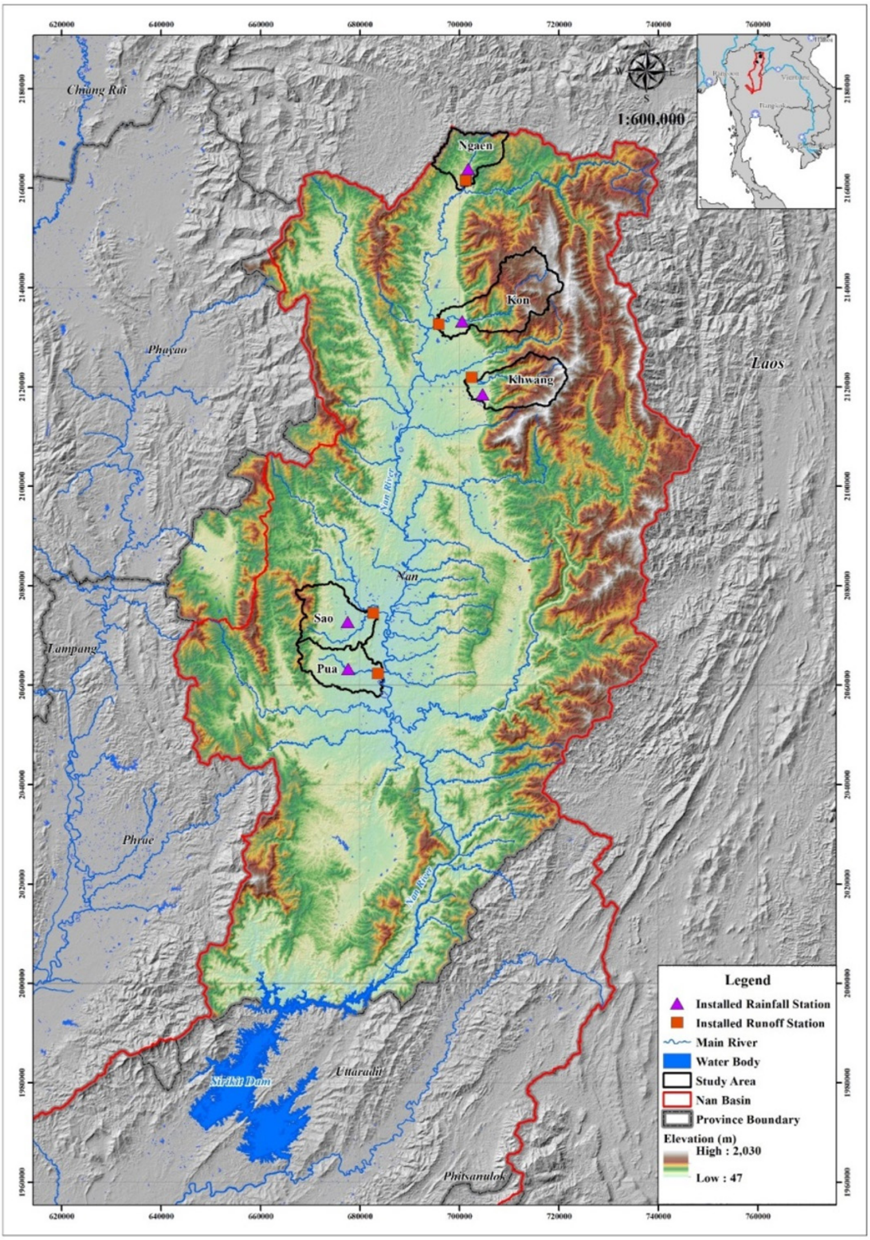


Figure 1. Location of the study area

Table 1. Physical characteristics of the watersheds in the study area

Parameter	Watershed				
	Ngaen	Kon	Khwang	Sao	Pua
Watershed area (km^2)	105.72	223.87	154.50	150.11	122.95
Watershed slope (%)	22.17	29.18	35.53	15.10	10.21
Field slope length (m)	15.24	15.24	15.24	24.38	60.96
Longest path (km)	18.41	37.21	25.86	25.74	25.83
Tributary reach slope (%)	3.53	3.57	6.26	2.66	2.15
Tributary reach width (m)	21.14	33.16	26.44	26.09	23.14
Tributary reach depth (m)	0.84	1.13	0.97	0.96	0.89
Average elevation (m)	564	897	854	370	288
Min elevation (m)	314	227	227	179	125
Max elevation (m)	991	1,771	1,905	1,106	914
Land use (%)					
Water Body	0.01	0.28	0.39	0.60	0.33
Orchard	0.44	4.98	3.70	4.09	20.18
Perennial Land	1.42	0.94	0.98	18.56	7.84
Swidden Cultivation	31.21	23.04	28.42	1.24	0.72
Paddy Field	0.18	3.87	5.05	13.10	12.16
Evergreen Forest	27.26	-	-	10.40	-
Deciduous Forest	36.78	61.91	55.79	27.13	23.81
Field Crop	2.26	2.49	1.39	18.49	29.42
Urban and Built-Up Land	0.42	2.08	3.13	5.73	2.37
Other	0.03	0.40	0.96	0.65	3.18
Forest Plantation	-	-	0.20	-	-
Soil Type (%)					
Slope Complex	97.75	87.22	86.97	47.60	22.39
Non-Slope Complex	2.25	12.78	13.03	52.40	77.61
Hydrologic Soils Groups (%)*					
Group A	-	-	-	9.90	35.01
Group B	2.25	10.67	9.53	20.33	32.62
Group C	97.75	88.28	88.12	63.08	26.74
Group D	-	1.05	2.35	6.69	5.64
CN-II **	78.62	78.89	79.59	75.84	69.09

Notes: * Hydrologic Soil Groups are classified by the Natural Resource Conservation Service based on the soil runoff potential. Group A generally has the smallest runoff potential, while group D has the greatest runoff potential.

** *CN-II* is the representative *CN* value of the watershed in the NRCS-CN method, which calculates from median *CN* in AMC-II conditions and λ equal to 0.2.

Source: Land use and soil group maps in 2016, Land Development Department.

2.2 Data collection

In the current study, the automatic rain gauges were developed and installed in each watershed area while the developed automatic water level gauges were installed at the outlet of the five study watersheds without the main river backwater affecting the measured water level. They measured and recorded rainfall data and water level every minute and then calculated the data gained as the continuous 10-minute average. Watershed runoff in cubic meters per second and rainfall data in millimeters were collected in the year 2018 for determining the initial abstraction (I_a) and the data for the year 2019 were used for parameter validation. The location of automatic rain gauges and automatic water level gauges were shown in Figure 1, while the pictures of gauges were shown in Figure S1 (Supplementary data).

2.3 Existing the NRCS-CN method

The NRCS-CN method is a conceptual model of hydrologic abstraction of storm rainfall, based on a simple mass water balance in Equation 1. The rainfall (*P*) is equal to the sum of the initial abstraction (I_a), infiltration (*F*) and runoff (*Q*). Two fundamental hypotheses that are the fundamental assumption of the NRCS-CN model are expressed in Equations 2 and 3. Equation 2 states that, after initial abstraction (I_a), the fraction of catchment storage, which is filled by infiltration (*F*), is equal to the fraction of available rainfall ($P - I_a$), that occurs as runoff (*Q*). Equation 3 relates the initial abstraction (I_a) to the initial abstraction ratio (λ) and the potential maximum retention after beginning of the runoff (*S*). (Shi *et al.,* 2009; Kowalik and Walega, 2015; Chin, 2017)

$$P = I_a + F + Q \quad (1)$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \quad (2)$$

$$I_a = \lambda S \quad (3)$$

When *P* is the depth of rainfall (mm), I_a is the initial abstraction (mm), which is defined as the rainfall depth that occurs before runoff begins or the amount of water before runoff, such as infiltration, or rainfall interception by vegetation. *F* is the cumulative infiltration excluding I_a (mm) or abstraction that occurs between when runoff begins and the rainfall event ends. *Q* is the depth of runoff (mm); *S* is the potential maximum retention of the catchment (mm) or potential maximum retention after the beginning of the runoff and λ is the initial abstraction ratio.

When combining Equations 1, 2 and 3 for expression of *Q*, it gives (Shi *et al.,* 2009)

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

Equations 4 is valid for $P > I_a$, otherwise, $Q = 0$. The parameter *S* in Equations 4 is defined as

$$S = \frac{25400}{CN} - 254 \quad (5)$$

where *CN* is the Curve Number which is mapped directly from catchment storage and estimated from hydrologic soil group of catchment soil, land uses and Antecedent Moisture Condition (AMC). AMC is the soil moisture condition at the beginning of a rainfall storm. It is sometimes referred to as antecedent runoff condition. AMC is divided into three conditions by the NRCS. AMC-I is for dry conditions that correspond to wilting point. It refers to the soil moisture conditions associated with the curve numbers of 90 exceedance frequency. AMC-II is for average conditions that correspond to soil moisture between wilting point and field capacity. It refers to the soil moisture condition associated with the median curve number or *CN-II*. AMC-III is for wet conditions that correspond to field capacity. It refers to the soil moisture conditions associated with the curve numbers of 10 exceedance frequency (Hjelmfelt, 1991; Wang *et al.,* 2012).

2.4 Creating a rainfall-runoff model

Based-on the NRCS-CN method, this research has analyzed the initial abstraction ratio (I_a/S) or λ for the rainfall of each event. The steps were as follows. First, find out the total runoff in mm by dividing the total runoff of each storm event by the watershed area. Second, separate observed hydrographs as direct runoff and base flow by using points of inflection of the rising limb and recession limb of hydrographs which indicated the beginning and end of the direct runoff, respectively. Third, determine the initial abstraction (I_a), which was equal to accumulated rainfall gained from the beginning of the storm events up to the time the direct runoff occurred. In each storm event, the total rainfall depth was known, leaving the unknown parameter merely the potential maximum retention (*S*), which was calculated from Equation 5. Finally, divide I_a by S to obtain the initial abstraction ratio or λ of each storm event. These steps were repeated in every single event in the process of data collection for a total of 80 events in the year 2018.

The NRCS-CN method performs better if the amount of water retained during runoff is a small fraction of rainfall. In other words, AMC-II or AMC-III implies that the retained water will be comparatively a smaller fraction of rainfall (Baltas *et al.,* 2007). Therefore, in this study, the selected events were tested by using the criteria of only days that rain exceeded 10 mm and was AMC-II.

The proposed calibrated watershed-specific NRCS-CN method in this study selected the median λ and the median S of the five watersheds based on the results of rainfall-runoff event analysis. After obtaining a median λ and median S value, I_a was calculated. Finally, the median λ and median S values were substituted into Equation (4) to form a calibrated watershed-specific runoff model.

The final step was to find the correlation between $S_{0.2}$ (derived from the original CN equation) and S obtained from the revised equation gained from the calibrated model which derived from rainfall-runoff data of five watersheds.

2.5 Runoff Model Assessment

The newly created rainfall-runoff model was also evaluated using 72 storm events in 2019. This includes the Nash-Sutcliff coefficient (*NSE*) (Nash and Sutcliffe, 1970), the coefficient of determination (R^2) and the percent of bias (*PBIAS*) as shown in equation 6, 7 and 8, respectively.

$$NSE=1-\frac{\sum_{i=1}^{n}(Q_{moi}-Q_{obi})^2}{\sum_{i=1}^{n}(Q_{obi}-\bar{Q})^2} \quad (6)$$

where n is the number of matched pairs of the model estimated and observed runoff, Q_{moi} and Q_{obi} are the model estimated and observed runoff for pair i and "$\underline{Q}$" is the average observed runoff over all n events. The coefficient of determination R^2 is

$$R^2=\left\{\frac{\sum_{i=1}^{n}(Q_{obi}-\overline{Q_{ob}})(Q_{moi}-\overline{Q_{mo}})}{\left[\sum_{i=1}^{n}(Q_{obi}-\overline{Q_{ob}})^2\sum_{i=1}^{n}(Q_{moi}-\overline{Q_{mo}})^2\right]^{0.5}}\right\}^2 \quad (7)$$

where $\underline{Q_{mo}}$ and $\underline{Q_{ob}}$ are the average model estimated and observed runoff over all n events. The *PBIAS* is

$$PBIAS=\frac{\sum_{i=1}^{n}(Q_{obi}-Q_{moi})}{\sum_{i=1}^{n}(Q_{obi})}\times 100 \quad (8)$$

3. Results and Discussion

3.1 Initial abstraction ratio based on rainfall-runoff storm events

The calculation of the initial abstraction ratio (λ) based on rainfall-runoff storm events was from a total of five watersheds comprised of Ngaen, Kon, Khwang, Sao and Pua. In total, 80 storm events in 2018 containing I_a and S values were derived from rainfall-runoff data pairs of these five watersheds and could be calculated as λ value. The analysis results showed that λ was between 0.032 - 0.077; the median λ was 0.045; S was between 25.763 and 149.161; the median S was 54.610 and I_a was between 1.330 and 7.458 as shown in Table S1 (Supplementary data) and Figure 2.

3.2 Watershed-specific NRCS-CN calibration method for five watersheds in the study area

A median λ value of 0.045 and a median S value of 54.61 mm resulted from the data gained from all the five watersheds, as seen in the rainfall-runoff event analysis in Table S1 (Supplymentary data). The next step was to calculate the median λ and median S. I_a can be computed using Equation 3. It was found that I_a was equal to 2.457 mm. Finally, the Ia and S values were substituted in Equation 4. Thus, based on the proposed watershed-specific NRCS-CN calibration method, the runoff depth (Q) for the five watersheds in the study area can be computed using Equation 9.

$$Q=\frac{(P-2.45745)^2}{P+52.15255} \quad (9)$$

3.3 Watershed-specific S Correlation Equation for five watersheds in the study area

When I_a changes, S and CN will change accordingly (Ling *et al.,* 2020). In this study, Equation 5 was used for data analysis by substituting λ, which equals to 0.045 and 0.200, with rainfall and runoff data in order to calculate S0.045 (the S value obtained from the assigned λ of 0.045) and $S_{0.20}$ (the S value obtained from the assigned λ of 0.2). The correlation equations of $S_{0.045}$ and $S_{0.20}$ for the five watersheds in the study area were also calculated.

Typically, the NRCS-CN direct runoff analysis is performed by selecting the *CN* value from the NEH handbook and calculating the *S* value with Equation (5) as proposed by NRCS under the hypothesis that I_a / S equals 0.20. This study used the reverse methodology to convert the $S_{0.045}$ value (λ equals 0.045 analyzed from median *S* for the five watersheds) into an equivalent $S_{0.20}$ (from the original equation that λ equals 0.2) value through a mapped watershed-specific *S* correlation equation in order to determine the watershed-specific *CN* ($CN_{0.20}$).

$$S_{0.2} = 0.4687\, S_{0.045}{}^{1.0599} \quad (10)$$

3.4 Runoff Model Assessment

The results of runoff model assessment gained from selected events with rainfall greater than 10 mm and AMC-II for average conditions combining a total of 72 events in the five watersheds. The data obtained from the measuring stations of rainfall-runoff in 2019 were compared to those calculated from the watershed-specific NRCS-CN method from Equation 9. The results of the assessment revealed the statistical values of the Nash-Sutcliff coefficient (*NSE*), the coefficient of determination (R^2) and the percent of bias (*PBIAS*) were 0.92, 0.92 and 1.91, respectively, as shown in Figure 3.

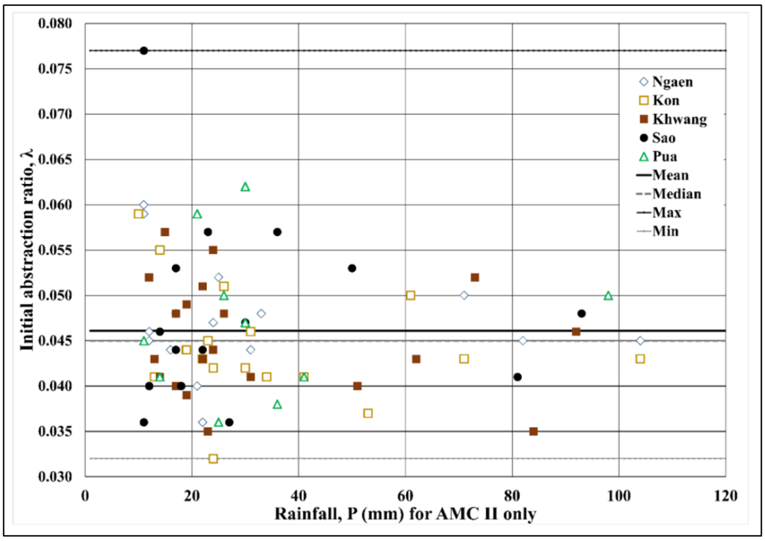
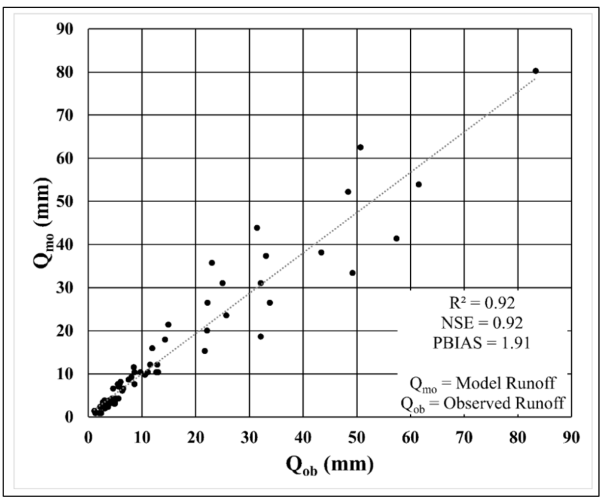


Figure 2. Initial abstraction ratio versus rainfall data of each event



Figures 3. Observed versus predicted runoff depth by the created model

The initial abstraction ratio (λ) in the NRCS-CN method was determined employing 2018-rainfall-runoff event analysis from five agricultural watersheds in the study area. The results indicated that λ was between 0.032-0.077 and the median λ was 0.045 pertaining to rainfall-runoff data of which the selected events with rainfall greater than 10 mm and AMC-II was for average conditions for a total of 80 storm events. The equation of watershed-specific NRCS-CN method was also created to calculate the runoff depth for the five watersheds. The results of the runoff model assessment which used the data obtained from the measuring stations of 2019-rainfall-runoff dataset compared to those calculated from the watershed-specific NRCS-CN method revealed high accuracy and met acceptance criteria with *NSE*, R^2 and *PBIAS* values of 0.92, 0.92 and 1.91, respectively. Regarding watershed-specific S correlation equation employed to determine the S correlation equation between $S_{0.045}$ and $S_{0.20}$ values for the five watersheds, R^2 was 0.97. This λ-modified NRCS-CN method from a model calibration in 2018 appears to be appropriate for runoff prediction in the five watersheds as shown from *NSE*, R^2 and *PBIAS* values of the dataset in 2019. According to the watershed areas used in this study, it is recommended that the created rainfall-runoff model can be used for further simulations in the tropically medium-sized watershed between 100 to 250 km² using NRCS-CN method and the $S_{0.2}$ from the fifth equation should be changed to $S_{0.045}$ as illustrated in the tenth equation. However, source code needs to be improved when using package programs like SWAT or SWMM.

4. Conclusion

The research revealed a median λ of 0.045 from five watersheds in northern Thailand, which have watershed area between 105.72 to 223.87 sq.km. The λ can be used in the NRCS-CN equation to estimate the rainfall-runoff in the area. Data were gathered from the rain-guages and water level gauge stationed in five watersheds in Nan river basin. 2018 storm data set were used to find the λ, and 2019 strom data were used to validate the λ. After the model validation using *NSE*, R^2 and *PBIAS* values of 0.92, 0.92 and 1.91 respectively, it portrayed that this λ provided more accurate result. It is concluded that this λ is recommened to be used for the future rainfall-runoff simulations in the 100 to 250 km² tropically medium sized watershed.

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