



Application of GIS-based Curve Number Method for Runoff Estimation in Agricultural-Forest Watershed, Thailand

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Abstract

The objective of this study was to apply the GIS-based hydrologic model for simulating runoff in the Upper Lam Ta Kong watershed, an agricultural-forest watershed, Nakhon Ratchasima province, Thailand. The Soil Conservation Service Curve Number (SCS-CN) method integrated with a Geographic Information System (GIS) was used to simulate the event-based runoff. Model calibration and validation were performed by comparing observed and simulated results at the M.43A and M.89 stations during the monsoon season of year 2011 and 2012, respectively. The runoff model calibration showed that the coefficient of efficiency (E) was 0.74 and coefficient of determination (R^2) was 0.83 at the M.43A while E was 0.73 and R^2 was 0.78 at the M.89 station. The results of the runoff model validation showed that the E was 0.66 and R^2 was 0.75 at the M.43A while E was 0.73 and R^2 was 0.87 at the M.89 station. This indicated that the GIS-based curve number method could be applied with satisfactory accuracy to runoff estimation in the study area. This model was also able to estimate varying runoff over the watershed spatially.

Keywords: *Runoff, GIS, SCS-CN, Upper Lam Ta Kong*

1. Introduction

Growing population, increasing urbanization, and climate change are shifting balance between water supply and demand, and impacting quality and quantity of water resources. Runoff information is required for watershed management purposes. The *in situ* measurement of runoff is considered more accurate but it cannot be operated anytime and anywhere as required. In Thailand,

the availability of accurate information on runoff is limited and there are only few selected sites where automatic and manual hydrologic gauging stations are installed. This conventional measurement is also expensive, time-consuming and difficult. Therefore, the accurate runoff modeling developed can serve this purpose with more convenient and less time consuming. Thus, the study on runoff simulation through hydrological modeling is necessary (1).

In terms of spatial domain, a model can be classified as a lumped or a distributed model. A lumped model is one in which it is typically assumed that rainfall and hydrological factors are uniform over the watershed. This causes the local characteristics and processes that affect the overall response of the system to be missed. To overcome this deficiency, a distributed model, in which the watershed divided into grid cells with spatially specific hydrologic parameters, was developed (2). Typically a uniform grid is used for computational convenience. Calculations are performed on discrete cells first and then accumulated over whole watershed based on drainage direction. Its principle advantage is that it can present more accurately the effects of spatial variability of watershed features on runoff estimation at different location within the watershed (3). Most of the hydrological models work best when data on the physical characteristics of the watershed are available at the model grid scale (4-6).

The SCS-CN method is widely used by engineers, hydrologists and watershed managers as a simple watershed model, and as the runoff estimating component in more complex watershed models. Generally, this method is well suited for small watershed, and it requires details of soil physical properties, land use, vegetation condition and rainfall data (7). In Thailand, previous research has been used lumped model at watershed scale (8-9). But, advances in computer power and the growing availability of GIS technology have made it possible to use hydrologic models like SCS-CN in spatial domain with remote sensing and GIS (10-13).

GIS is computer-based tool that displays, stores, analyzes, retrieves and generates spatial and non-spatial data, which an important tool in analysis of

parameters such as land use, land cover, soils, topographical and hydrological conditions (14). The use of this advanced tool, along with hydrologic models, results in more accurate runoff simulation. This can be useful in spatial variability for watershed management purposes. The objective of this study was to apply the GIS-based hydrologic model for simulating runoff to support watershed management in the upper Lam Ta Kong watershed.

2. Materials and methods

2.1 Study area

The upper Lam Ta Kong watershed covers an area of 1,241 km² in Nakhon Ratchasima province (Figure 1). The study area lies between latitudes 14° 23' 07" N to 14° 51' 53" N and longitudes 101° 16' 27" E to 101° 44' 09" E. The topography of the area is characterized by generally hilly-rolling terrain, with less undulating area. Elevation ranges from 255 m above mean sea level (msl.) in the northeastern parts to about 1,330 m above msl. in the southwestern parts of the watershed. The weather is characterized by monsoon tropical climate with dry and wet seasons. The wet season starts from mid-May to October but its intensity increases in June to August and subsides in mid-September. The dry season starts from November to April. The average annual rainfall is about 960 mm. The soil in the area varies in 24 series with different soil textures such as clay, sandy loam, loamy sand, clay loam, silty clay, sandy clay loam, loam. The upper Lam Ta Kong watershed is the upstream area of the Lam Ta Kong dam. In 2012, more than 32.23% of watershed was classified as forests which were evergreen forest and deciduous forest. The 28.74% of the area was classified as field crop.

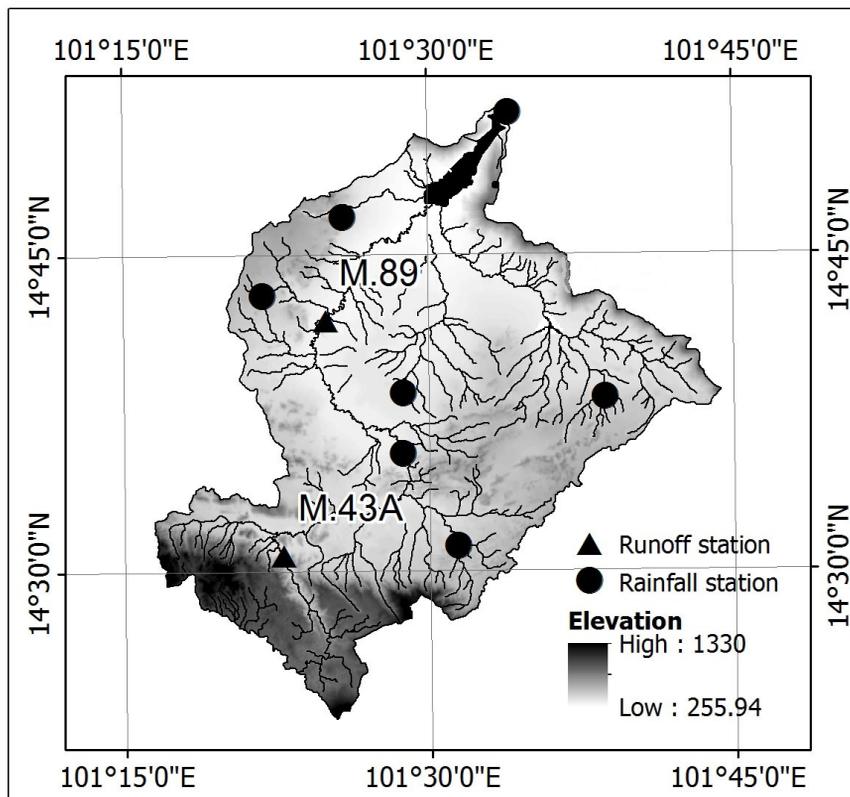


Figure 1. Map of the study area.

2.2 Data collection

The Royal Irrigation Department (RID) provided rainfall data of the year 2011 and 2012 with 7 manual rain gauges, located within the watershed. Spatial variation of rainfall was computed by using the Kriging interpolation method. Topographic maps of Royal Thai Survey Department (RTSD) at the scale of 1:50,000 were used to generate Digital Elevation Model (DEM). For the model, relevant parameters generated from DEM were flow direction and flow accumulation. Flow direction was extracted from DEM based on the D8 algorithm (15). Observed runoff data of the RID hydrological station, M.43A with 153 km² drainage area at the upstream outlet and M.89 with 713 km² drainage area

at downstream outlet, are used for model calibration and validation. The soil properties and soil map at scale 1:25,000 were obtained from Land Development Department (LDD). The soils were reclassified into hydrologic soil groups (HSG) (Figure 2) according to the infiltration rate, which was calculated from soil texture properties based on criteria provided by National Resources Conservation Service (NRCS) (16). The land use data (Figure 3) at scale 1:4,000 were obtained from LDD and update to the year 2012 by using Thailand Earth Observation System (Thaichote or THEOS) satellite imagery data. All GIS data were projected to the UTM WGS 1984 Zone 47N coordinate system.

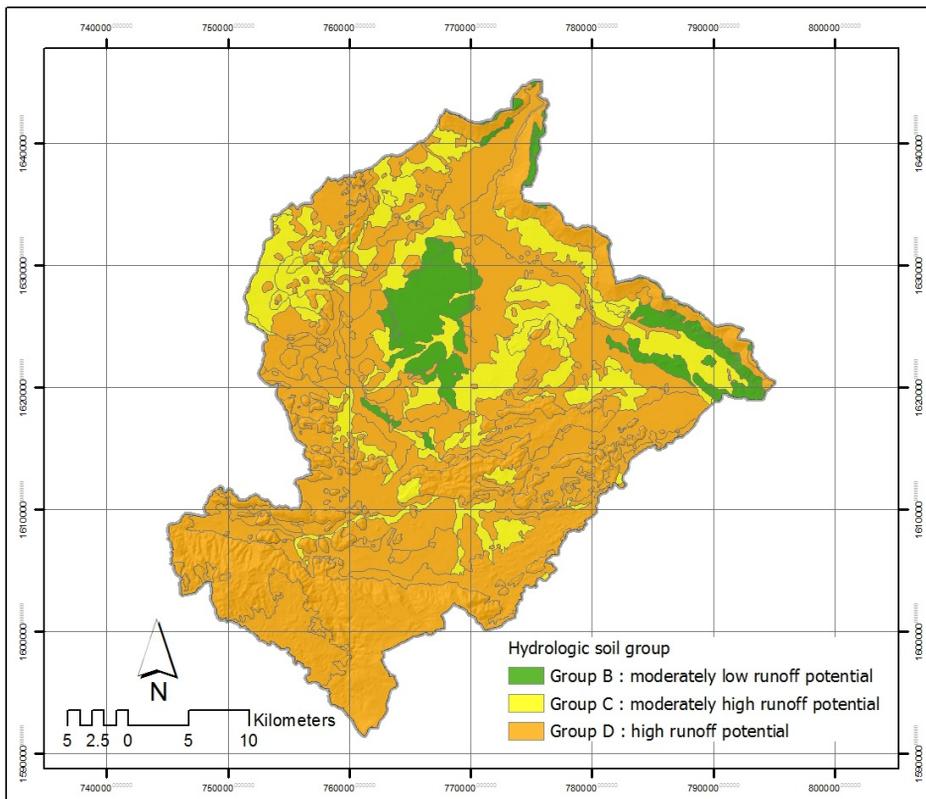


Figure 2. Hydrologic soil group.

2.3 SCS-CN method

The SCS-CN method is based on the water balance equation and two fundamental hypotheses (17). The first hypothesis equates the total rainfall (P ; or maximum potential runoff) to summation of actual amount of direct runoff (Q), the amount of actual infiltration (F), and the initial abstraction (I_a). The second hypothesis shows the relationship between I_a and the amount of the potential maximum retention (S). Thus, the SCS-CN method is consists of the following equations (18):

1) Water balance equation

$$P = I_a + F + Q \tag{1}$$

2) Proportional equality hypothesis

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{2}$$

3) $I_a - S$ hypothesis

$$I_a = \lambda S \tag{3}$$

where, P is the total rainfall; I_a is the initial abstraction; F is the cumulative infiltration excluding I_a ; Q is the direct runoff; S is the potential maximum retention of infiltration; and λ is the regional parameter dependent on geologic and climate factors ($0.1 \leq \lambda \leq 0.3$). Combining the water balance equation and proportional equality hypothesis, the CN method is represented as:

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

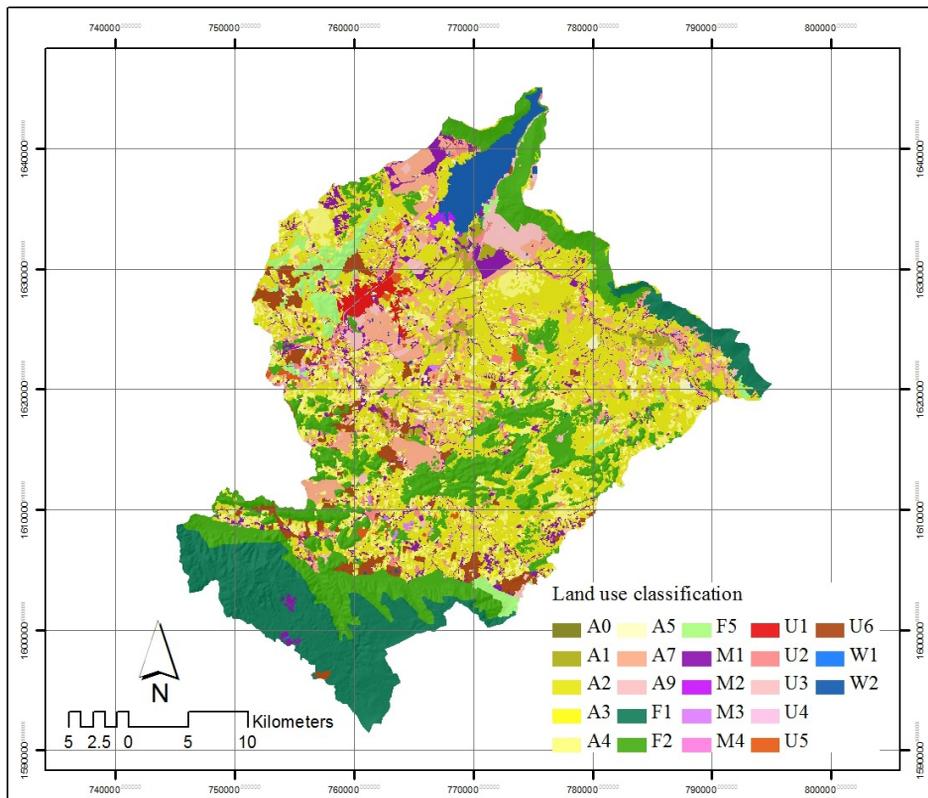


Figure 3. Land use map.

The potential maximum retention storage (S) of watershed is related to a curve number, which is a function of land use, land treatments, soil type and antecedent moisture condition of watershed. Curve number is dimensionless and its value varies from 0 to 100. The S value in mm units can be obtained from CN by using the relationship:

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

where S is in mm and CN is the curve number values, which varies based on a function of land use, land treatment, hydrologic soil group, and antecedent moisture condition (AMC) of a watershed.

A combination of these is a hydrologic soil cover complex. The CN values were assigned to each grid cell to such complex to indicate their specific runoff potential.

The CN values were adjusted based on AMC. AMC is an indicator of watershed wetness and availability of soil storage prior to a storm. Three level of AMC are used: AMC-I for dry, AMC-II for normal and AMC-III for wet conditions. The CN values were adjusted based on the season and 5-day antecedent precipitation. Mathematically, adjustment to CN values for the cases of AMC-I and AMC-III, the following equation are used (19):

$$CN_I = \frac{4.2CN_{II}}{10 - 0.058CN_{II}} \quad (6)$$

$$CN_{III} = \frac{23CN_{II}}{10 - 0.13CN_{II}} \quad (7)$$

2.4 Model setup

The SCS-CN method is one of the most widely used methods for quick and accurate estimation of runoff. The coupling of the SCS-CN method with the GIS capabilities automates the process of runoff simulation in a timely and efficient manner. The tools were applied based on the grid-based or raster-based operation of GIS-processes. All GIS layer of hydrological factors were prepared in raster format with grid cell size of 30 x 30 m. Each cell homogenously represented characteristics of the hydrological factors. The computer program ModelBuilder™ of ArcGIS™ was used to create the model toolbox with a required set of spatial analyses. The runoff depth in each grid cell was computed using the SCS-CN method, and then routed through the watershed based on flow direction and flow accumulation from one grid cell to next until it reached the watershed outlet. The simulation values were picked up from cells located at M.43A and M.89 stations. The outputs of model simulations and observed values of all events at these two cells were tabulated to estimate the statistical indices for model evaluation.

2.5 Model evaluation

The model evaluation procedure included calibration and validation. The runoff model used 21 (year 2011) and 17 (year 2012) rainfall events of monsoon season for calibration and validation, respectively. In each calibration step the simulation result of runoff was compared to actual ones of selected events observed from M.43A and M.89 stations. The

parameter providing the most fit of simulation and observation of events were taken for the model operation. To evaluate the calibrated model, the optimized parameters for the other events were used for model validation. The agreement between the simulation and observation results for selected events were assessed by using coefficient of determination (R^2) and Nash-Sutcliffe coefficient of efficiency (E).

The R^2 measures the linear dependence of observed and simulated values. The E (20) is one of the indices most frequently used to assess hydrological models. It can be expressed as follows:

$$E = 1 - \frac{\sum_{i=1}^N (Obs - Sim)^2}{\sum_{i=1}^N (Obs - \overline{Obs})^2} \quad (8)$$

where obs is the observed value; sim is the simulated value; and \overline{obs} is the mean of the observed values. The E value can vary from $-\infty$ to 1. $E = 1$ means that there is complete agreement between the observation and simulation. A negative value of E means that forecast is not satisfactory: a long-term average of the observed quantity is better than the model outputs.

3. Results and discussion

3.1 Runoff estimation

Results of the runoff model calibration and validation are displayed in Tables 1 and 2. Twenty one selected events were used for model calibration. Another 17 events were used for model validation. The total runoff estimation or simulation of 21 calibration events through M.43A and

M.89 were 148.60 mm and 54.29 mm, respectively, while for the observations they were 189.08 and 67.62 mm, respectively. The total runoff estimation of 17 validation

events through M.43A and M.89 were 57.35 mm and 11.43 mm, respectively, while for the observations they were 73.29 mm and 19.99 mm, respectively.

Table 1. The results of runoff model calibration events.

| Calibration events | AMC | Rainfall (mm) | Runoff depth (mm) | | | |
|-----------------------|--------|---------------|-------------------|------------------|------------------|------------------|
| | | | M.43A | | M.89 | |
| | | | Q _{obs} | Q _{sim} | Q _{obs} | Q _{sim} |
| 2011/04/28 | dry | 17.8 | 1.55 | 1.03 | 0.47 | 0.14 |
| 2011/05/25 | dry | 16.7 | 0.9 | 0.14 | 0.93 | 0.11 |
| 2011/05/27 | dry | 24.9 | 1.07 | 1.09 | 0.93 | 0.33 |
| 2011/05/28 | wet | 51.7 | 1.55 | 0.92 | 0.88 | 3.55 |
| 2011/07/31 | dry | 27.2 | 8.98 | 9.02 | 1.83 | 0.20 |
| 2011/08/14 | dry | 23.7 | 4.24 | 3.04 | 1.08 | 0.41 |
| 2011/08/15 | dry | 22.1 | 5.36 | 6.03 | 1.98 | 0.18 |
| 2011/08/19 | normal | 6.6 | 11.41 | 9.01 | 2.27 | 2.08 |
| 2011/09/08 | dry | 14.0 | 4.74 | 2.04 | 1.35 | 1.11 |
| 2011/09/09 | dry | 55.7 | 5.59 | 7.19 | 1.49 | 1.32 |
| 2011/09/10 | wet | 66.2 | 17.72 | 12.01 | 4.06 | 4.60 |
| 2011/09/11 | wet | 34.0 | 28.11 | 20.57 | 11.21 | 8.21 |
| 2011/09/13 | wet | 8.3 | 28.89 | 19.02 | 9.79 | 7.23 |
| 2011/09/22 | dry | 5.8 | 6.78 | 8.08 | 2.05 | 1.16 |
| 2011/09/23 | dry | 12.6 | 7.62 | 4.04 | 2.14 | 1.10 |
| 2011/09/26 | normal | 57.6 | 10.84 | 12.91 | 4.91 | 2.96 |
| 2011/10/03 | normal | 34.2 | 6.95 | 4.09 | 4.48 | 3.91 |
| 2011/10/05 | normal | 19.9 | 7.79 | 5.08 | 3.54 | 2.25 |
| 2011/10/10 | dry | 9.6 | 11.21 | 5.08 | 2.56 | 1.15 |
| 2011/10/13 | dry | 6.5 | 10.33 | 14.07 | 6.36 | 7.14 |
| 2011/10/15 | dry | 9.7 | 7.45 | 4.14 | 3.31 | 5.14 |
| Total | | | 189.08 | 148.60 | 67.62 | 54.29 |
| <i>E</i> | | | | 0.74 | | 0.73 |
| <i>R</i> ² | | | | 0.83 | | 0.78 |

Table 2. The results of runoff model validation events.

| Validation events | AMC | Rainfall (mm) | Runoff depth (mm) | | | |
|-------------------|--------|---------------|-------------------|-----------|-----------|-----------|
| | | | M.43A | | M.89 | |
| | | | Q_{obs} | Q_{sim} | Q_{obs} | Q_{sim} |
| 2012/05/15 | dry | 38.4 | 0.02 | 0.04 | 0.18 | 0.45 |
| 2012/06/07 | dry | 18.6 | 0.82 | 0.63 | 0.27 | 0.33 |
| 2012/07/26 | dry | 12.5 | 0.73 | 0.44 | 0.23 | 0.59 |
| 2012/08/09 | dry | 5.0 | 0.55 | 0.1 | 0.19 | 0.16 |
| 2012/08/18 | dry | 7.0 | 0.90 | 0.49 | 0.21 | 0.1 |
| 2012/08/25 | dry | 10.9 | 2.09 | 2.1 | 0.48 | 0.13 |
| 2012/08/26 | dry | 2.2 | 6.04 | 4.1 | 0.42 | 0.25 |
| 2012/09/05 | dry | 9.3 | 1.86 | 1.04 | 0.48 | 0.1 |
| 2012/09/06 | dry | 22.9 | 3.44 | 3.05 | 0.56 | 0.13 |
| 2012/09/15 | dry | 21.9 | 5.25 | 7.02 | 0.72 | 0.9 |
| 2012/09/16 | dry | 23.8 | 5.82 | 6.04 | 1.28 | 0.15 |
| 2012/09/20 | normal | 24.0 | 5.36 | 6.15 | 1.41 | 0.45 |
| 2012/09/23 | dry | 19.4 | 6.61 | 5.03 | 2.98 | 1.09 |
| 2012/09/26 | dry | 52.8 | 5.93 | 4.03 | 1.74 | 1.18 |
| 2012/09/27 | wet | 7.6 | 16.23 | 8.04 | 6.62 | 5.12 |
| 2012/10/07 | dry | 13.4 | 3.56 | 2.02 | 0.98 | 0.11 |
| 2012/10/08 | normal | 23.6 | 8.08 | 7.03 | 1.24 | 0.19 |
| Total | | | 73.29 | 57.35 | 19.99 | 11.43 |
| E | | | | 0.66 | | 0.73 |
| R^2 | | | | 0.75 | | 0.87 |

3.2 Runoff model calibration and validation

A part of the calibration procedure for the runoff model was done by adjusting the “ λ ” values in Eq. 3 in such manner that the calculated E for all calibration events would be highest. The calibration results showed that the model could provide the best simulated results with $E = 0.74$ and

$R^2 = 0.83$ for M.43A station and $E = 0.73$ and $R^2 = 0.78$ for M.89 station when adjusting $\lambda = 0.2$. The validation results showed that $E = 0.66$ and $R^2 = 0.75$ for M.43A station and $E = 0.73$ and $R^2 = 0.87$ for M.89 station. The spatial variation of the event-based simulated runoff depths used for validation was displayed in Figure 4.

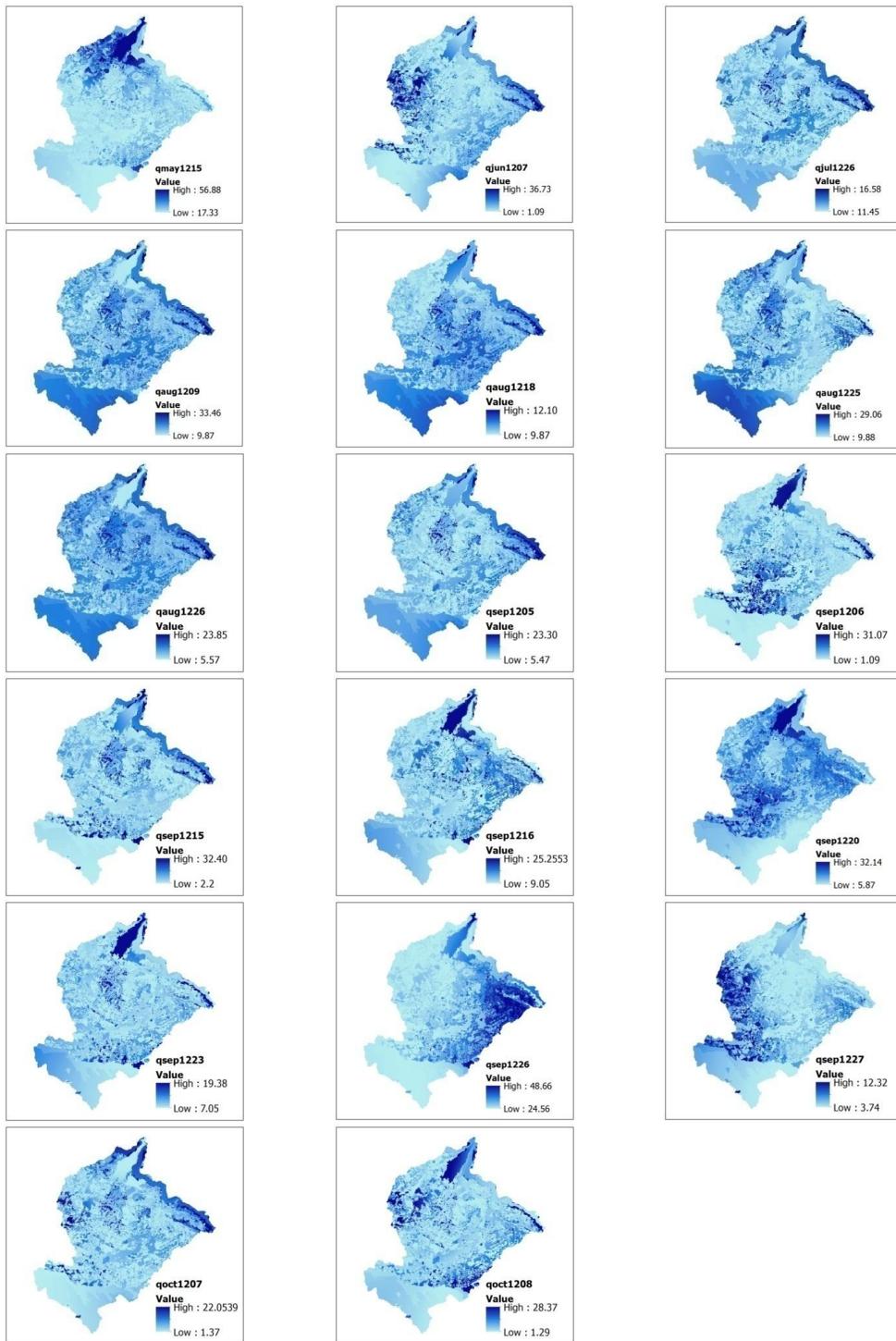
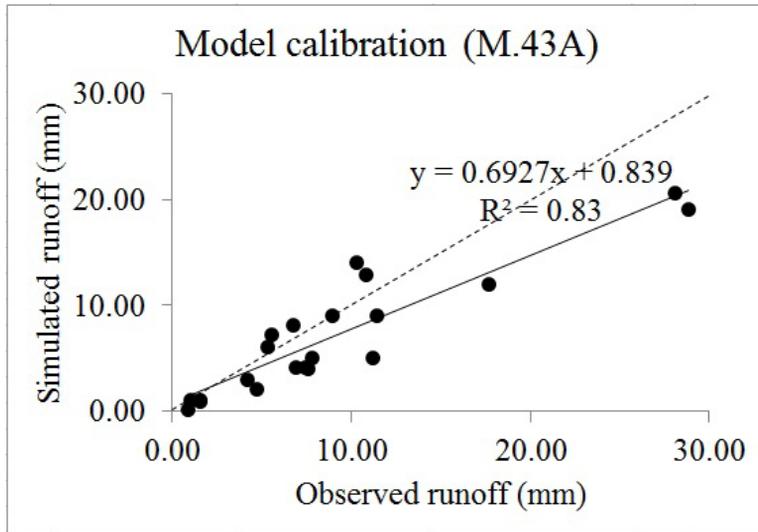
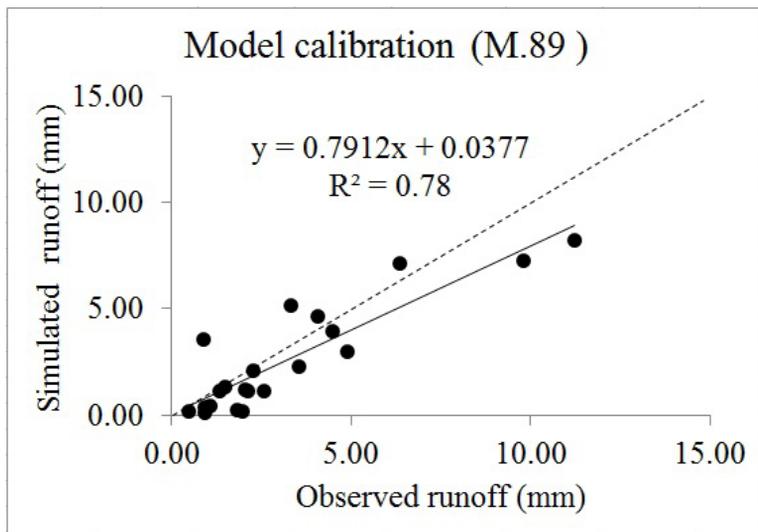


Figure 4. The spatial variation of event-based simulated runoff depths (mm) used for validation.

Comparison between observed and simulated runoffs for calibration and validation are shown in Figures 5 and 6, respectively.



A) M.43A station.

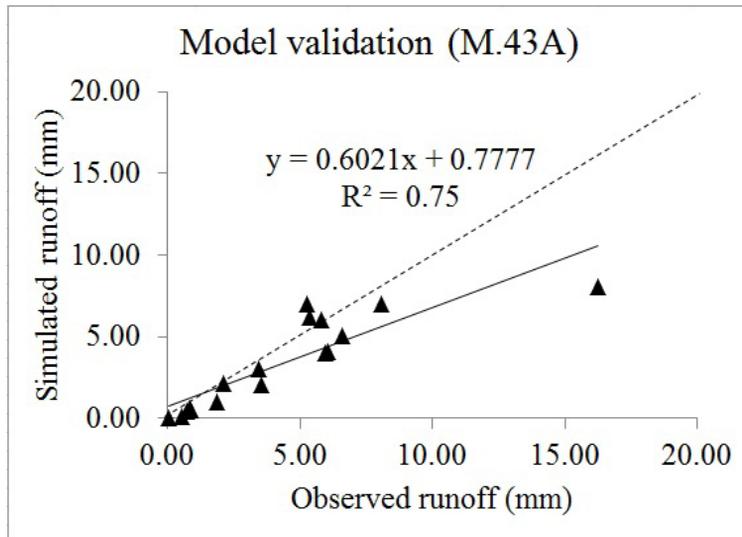


B) M.89 station.

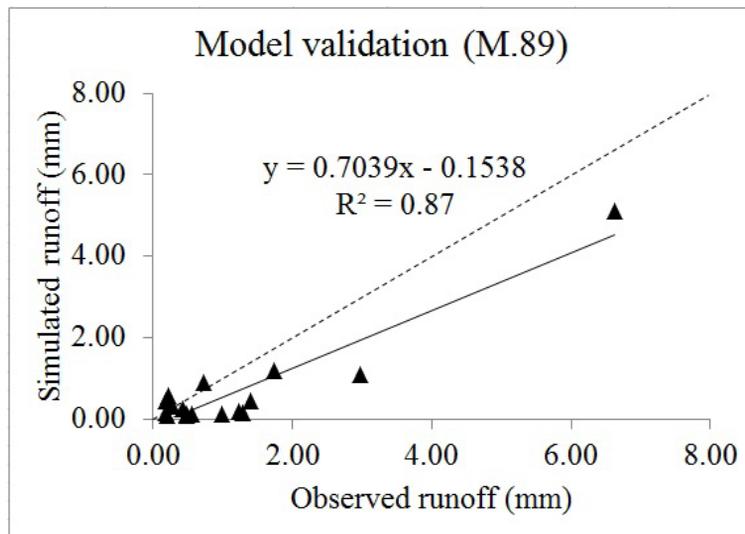
Figure 5. Comparison of observed and simulated runoffs for calibration.

From scatter plot of observed and simulated runoffs for calibration it is observable that, compared to the observed values at the M.43A station, the simulated values are slightly below the 1:1 line, indicating that the model has slight underestimation. Meanwhile, compared to

the observed values at the M.89 station, the simulated values are slightly below the 1:1 line, indicating that the model has slight underestimation. It can be concluded that the comparison results at both the M.43A and M.89 stations, as shown in the scatter plot are quite satisfactory.



A) M.43A station.



B) M.89 station.

Figure 6. Comparison of observed and calibrated-simulated runoffs for validation.

From the comparison scatter plot of the observed and calibrated-simulated runoffs for validation, it is observable that at the both stations the model has a slight underestimation as the relation line is slightly below the 1:1 line. However, the scatter plot of M.89 downstream station was better distributed than that of M.43A

upstream station. The error encountered at both stations could be explained by the models really providing every cell simulation and accumulating them from upstream to the cells at the station while the actual processes were hardly able to exist in all cells, especially water usage activities along with the Lam Ta Kong stream.

4. Conclusion

The study was to apply the GIS-based Curve Number method for simulation of runoff from upper Lam Ta Kong watershed, an agricultural-forest watershed, Nakhon Ratchasima province, Thailand. Grid-based computation was used to simulate the runoff. Inclusion of the distributed spatial characteristics provided a significant advantage in the modeling compared with the lumped model.

The runoff processes locally worked on spatial variation of features which are land use, HSG, rainfall, and topographic characteristics, leading to runoff potential assessment. The E and R^2 were used for the model performance evaluation. These ranged were from 0.66 to 0.73 and 0.75 to 0.87, respectively. As a result of the case study at the agricultural-forest watershed, it can be confirmed that the GIS-based Curve Number method is applicable to runoff estimation and is effective. Not only the satisfactory results provided but the model was also to estimate varying runoff over the watershed spatially.

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