RUNOFF AND SEDIMENT YIELD ESTIMATION USING DISTRIBUTED GEOSPATIAL MODELS FOR AGRICULTURAL WATERSHED IN THAILAND

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Abstract

This study aims at developing distributed geospatial models to simulate runoff and sediment yield for Upper Lam Phra Phloeng, an agricultural watershed in Thailand. The soil conservation service curve number method, the modified universal soil loss equation, and the sediment delivery distributed model integrated with a geospatial model were used to simulate the event-based runoff and sediment yield. Calibration and validation were performed by comparing observed and simulated results at the M.171 and M.145 stations during the rainy season of the year 2008. The runoff model calibration shows that the coefficient of efficiency (E) is 0.94 and coefficient of determination (R^2) is 0.95 at the M.171 station while E is 0.87 and R^2 is 0.91 at the M.145 station. The results of the runoff model validation show that E is 0.87 and 0.68 and R^2 is 0.89 and 0.75 at M.171 and M.145 stations, respectively. The sediment yield model calibration results show that E is 0.85 and R^2 is 0.89 while its validation shows that E and R^2 are 0.79 and 0.92, respectively. This indicates that the calibrated model working under the geographic information system (GIS) can be applied with satisfactory accuracy to the runoff and sediment yield estimation. Not only are the quantitative results provided satisfactory, but the model is also able to estimate varying runoff and sediment yield over the watershed spatially.

Keywords: Runoff model, Sediment yield model, Distributed geospatial model, GIS

Introduction

Runoff and sediment yield information is required for watershed management purposes. Reliable estimation of the amounts from the land surface into streams and reservoirs is difficult, expensive, and time-consuming. The *in situ* measurements of them are considered more accurate but cannot be operated at any time and anywhere as required. In Thailand, the availability of accurate information on runoff and sediment

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yield is limited and there are only a few selected sites where automatic hydrologic gauging stations are installed. Thus, the study on their simulation through hydrological modeling is necessary.

In terms of spatial domain, a model can be classified as a lumped or a distributed one. A lumped model is one in which it is typically assumed that rainfall and hydrologic 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 geospatial model, in which the watershed is divided into grid cells with spatially specific hydrologic parameters, was developed (Olivera and Maidment, 1999). Typically a uniform grid is used for computational convenience. Calculations are performed on discrete cells first and then accumulated over the whole watershed. Its principle advantage is that it can present more accurately the effects of spatial variability of watershed features on runoff and sediment yield estimation at different locations within the watershed. However, it requires a large amount of data. With advances in computer technology, distributed models are gaining popularity (Pullar and Springer, 2000; Merritt *et al.*, 2003). Remote sensing (RS) and GIS can provide valuable and up-to-date spatial information on hydrologic factors and physical terrain parameters for a spatially distributed model. GIS also provides a generic tool to derive the result from primary data collected over the watershed. The use of this advanced tool, along with process-based hydrologic models, results in more accurate runoff and sediment yield simulations. This can be useful in spatial variability for watershed management purposes.

Several studies have been done to incorporate GIS and RS into runoff and sediment yield modeling of watersheds. These studies have different scopes and can be generally grouped into 3 categories. Computation of input parameters for existing models (Olivera and Maidment, 1999; Anbazhagan *et al.*, 2005; Pandy *et al.*, 2008; Cho *et al.*, 2008; Amutha and Porchelvan, 2009; Rao *et al.*, 2010) refers to uses of GIS in the representation of watershed surface through the use of a digital elevation model (DEM) and gridded geographic data. Unlike lumped models, distributed models require large amounts of spatial data, which can be computed using GIS. An integrated existing model with GIS platform (He, 2003; Zhan and Huang, 2004; Huang *et al.*, 2008 Patil *et al.*, 2008; Strager *et al.*, 2010) refers to a developed GIS integrated/coupled with existing model simulation for which it is easy for the user to prepare the input data, run the models, and visualize the result. Pullar and Springer (2000) reviewed different aspects of an integrated watershed model with GIS. Hydrologic assessment (Melesse and Shih 2002; Najim *et al.*, 2006; Xinxiao *et al.*, 2009) refers to the mapping and displaying in GIS of hydrologic factors that pertain to a situation. In all of these studies, the potential of RS and GIS in runoff and sediment yield modeling has been clearly demonstrated.

From the literature, studies on the modeling using RS and GIS to explore the environmental problem from runoff and sediment yield in Thailand's watersheds are very few. The techniques for runoff and sediment yield simulation need to be established. These techniques would help identify areas which contribute to higher runoff and sediment yield. To address their spatial variability, the study considered them to be spatially distributed. The objective of this study was to develop the geospatial models for simulating runoff and sediment yield to support watershed management in the Upper Lam Phra Phloeng watershed.

Materials and Methods

Study Area

The Upper Lam Phra Phloeng watershed covers an area of 786 km^2 in Nakhon Ratchasima Province, Thailand (Figure 1). The study area lies between latitudes 14º 18´ 24” N to 14º 38´ 30” N and longitudes 101º 28´ 52” E to 101º

54´ 09” E. The topography of the area is generally characterized by hilly and rolling terrain, with fewer undulating and flat areas. Elevation ranges from 260 m above mean sea level (msl.) in the northeastern parts to about 1307 m above msl. in the southwestern parts of the watershed. The climate is influenced by both the northeast and southwest monsoons, with average rainfall of 1117 mm. The soil in the area varies in 15 series with different soil textures such as clay, clay loam, loam, loamy sand, sandy clay loam, sandy loam, and silty clay. The watershed experiences extensive farming and has no large towns. The Upper Lam Phra Phloeng watershed is the upstream area of the Lam Phra Phloeng reservoir. Therefore, any activities present in the area can affect the downstream reservoir. Lam Phra Phloeng reservoir is the highest sedimentation reservoir in northeastern Thailand (Tangtham and Lorsirirat, 1993). Its storage capability was decreased from 150 million cubic meters to 108 million cubic meters during 1970-1991. Sedimentation is mostly associated with agricultural activities, especially when crops were increased from 44.97 to 65.49 percent of the area during 1973-2000 (Charuppat, 2002). In 2007, more than 41.52% of the watershed was classified as dominant crops which were maize, sugarcane, and cassava. Only 24.83% of the area was classified as forests. In order to preserve natural resources and the useful life of the reservoir, it is necessary to identify the critical areas in the watershed that contribute higher runoff and sediment yield.

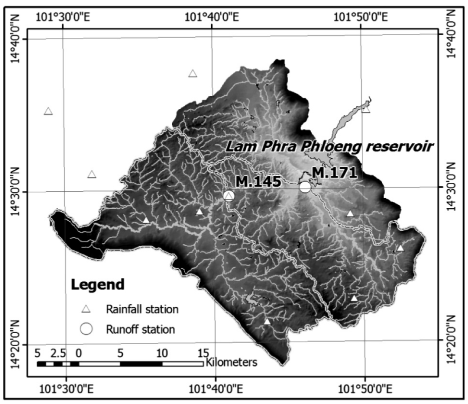

Figure 1. Location of the Upper Lam Phra Phloeng watershed and the M.171 and M.145 gauge stations

Runoff and Sediment Yield Observation

Field observations of runoff and sediment yield based on events in the monsoon period between June–October 2008 were conducted at M.145 and M.171 gauge stations, which cover 335 km^2 and 556 km^2 of the upstream areas, respectively. The measurements were confined to the stream flow and sediment yield measurements. The observed runoffs and sediment yields for different rain events were used to evaluate the model simulation by result comparison.

Event-based suspended sediment sampling was conducted by the depth integrating method. Subsamples were taken at various depths and distances from the stream bank and integrated into a single sample. The collection of sediment samples was attempted to coincide with the runoff peaks, and also temporally over the rising and descending portion of the hydrograph curve. Prior to collecting a sample, measurement of the stream flow was conducted. The suspended sediment concentration samples were then analyzed after drying at 103°C. The amount of total sediment yield was then calculated based on the sediment concentration and runoff volume.

Data Collection for Modeling

The Royal Irrigation Department has provided rainfall data from 11 manual rain gauges, located within and near the watershed. Spatial variation of rainfall was computed using the inverse distance weighted interpolation method. Event-based rainfall data were used as an initiatory driving force of the models. Topographic maps of the Royal Thai Survey Department at the scale of 1:50,000 were used to generate DEM data. For the models, relevant parameters generated from DEM data were flow accumulation, flow length, and slope. Flow lines were extracted from DEM data based on the D8 algorithm (O'Callaghan and Mark, 1984). The soil properties and soil map at the scale 1:25000 were obtained from the Land Development Department (LDD). However, this data set has no information on complex slope areas. Therefore, data from geological information of the Department of Mineral Resources were derived and used for complementing where soil data are absent. The soils were reclassified into hydrologic soil groups (HSG) according to the infiltration rate, which was calculated from soil texture properties based on criteria provided by the National Resources Conservation Service (NRCS) (2007). The soil erodibility factor was calculated from the soil physical properties. The digital land use data at scale 1:25000 obtained from the LDD were updated to the year 2007. The model simulation was conducted in 2008. This study assumed that there was little change in land use between 2007 and 2008. Each GIS layer of the model input data was prepared in raster format with a grid cell size 30×30 m. All GIS data were projected to the UTM WGS 1984 Zone 47N coordinate system.

Application of Runoff Model

The soil conservation service curve number (SCS-CN) method is one of the most widely used methods for quick and accurate estimation of surface runoff. Also, the coupling of the SCS-CN technique with the GIS capabilities automates the process of runoff simulation in a timely and efficient manner. The SCS-CN method was developed to estimate total storm runoff from total storm rainfall. This method estimates direct runoff, which consists of channel runoff, surface runoff, and an unknown proportion of subsurface runoff. The SCS-CN method is based on the water balance equation and 2 fundamental hypotheses (NRCS, 2004). The first hypothesis equates the total rainfall (*P*; or maximum potential surface runoff) to the actual amount of direct surface runoff (*Q*), the amount of actual infiltration (*F*), and the initial abstraction (I_a). The second hypothesis shows the relationship between Ia, and the amount of the potential maximum retention (*S*). Thus, the SCS-CN method consists of the following equations (Mishra and Singh, 2003):

(a) Water balance Equation

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

(b) Proportional equality hypothesis

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

(c) I_a-S hypothesis

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

where *P* is the total rainfall; I_a is the initial abstraction; *F* is the cumulative infiltration excluding I_a; *Q* is the direct surface runoff; *S* is the potential maximum retention; and λ is the regional parameter dependent on the geological and climate factor ($0.1 \leq \lambda \leq 0.3$). The I_a consists mainly of interception, infiltration, antecedent soil moisture and depression storage, all of which occur before surface runoff begins (Grunwald and Norton, 2000). Combining the water balance equation and the proportional equality hypothesis, the runoff equation is presented as:

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

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

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

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. Mohammed *et al.* (2004) suggested that the *CN* values comprise the most sensitive parameter and should be carefully determined through field assessment based on local conditions such as cultural practices, land use, and topography.

Soils of the study area are classified into 3 HSG (B, C, and D) (Figure 2) according to their minimum infiltration rate, which is obtained for a bare soil after prolonged wetting. Soils in group B have moderately low runoff potential, soils in group C have moderately high runoff potential, and group D soils have the highest runoff potential. The land cover complex classification depends on 3 factors: land use, treatment, and hydrologic condition. Land use (Figure 3) includes all agricultural and non-agricultural lands. Land treatment refers mainly to mechanical practices (e.g. contouring or terracing) and management practices (e.g. grazing control, crop rotation, or conservation tillage). The hydrologic condition reflects the level of land treatment and is divided into 3 classes: poor, fair, and good (Melesse and Shih, 2002). The AMC is an indicator of watershed wetness and availability of soil storage prior to a storm. The AMC is determined by the cumulative total of the last five days' rainfall. Three levels of AMC are used: AMC-I for dry, AMC-II for normal, and AMC-III for wet conditions. Many hydrological models have been developed based on the SCS-CN method, because of its simplicity, relative ease of use, and availability of information for estimation of the *CN* values.

Soil erosion is a hydrologically driven process and it depends on sediment being discharged with runoff (Kinnell, 2005). By including the runoff as an independent factor in modeling erosion, the modified universal soil loss equation (MUSLE) has an improved accuracy of soil erosion prediction over the USLE and the revised USLE, which do not include the runoff factor. In general, the MUSLE can be expressed as follows (Williams, 1975):

$$Y = a(Q \times q_p)^b K \times LS \times C \times P \tag{6}$$

where Y is the total soil loss in metric tons, Q is the runoff volume from a given rainfall event in m^3, q_p is peak flow rate in m^3s^{-1}, K is the soil erodibility factor (Figure 4), LS is the slope length and slope steepness factor (Figure 5), C is the cover management factor (Figure 6) derived from the land use data, P is the erosion control practice factor (Figure 7) which is a field specific value, and a and b are location coefficients. For the area where the equation was developed, a and b were 11.8 and 0.56, respectively.

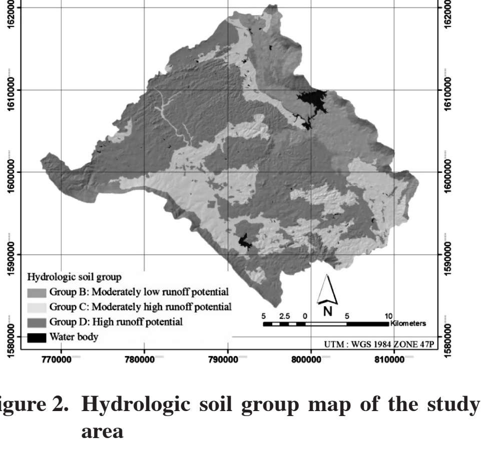

Figure 2. Hydrologic soil group map of the study area

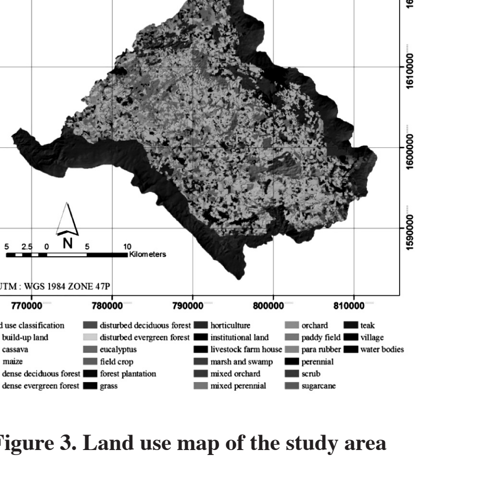

Figure 3. Land use map of the study area

Sediment Yield Estimation

The sediment delivery ratio (SDR) is most commonly defined as the ratio of sediment yield to total soil loss. Ferro and Porto (2000) proposed the sediment delivery distributed (SEDD) model for the variability of the sediment delivery process within a watershed by calculating the SDR per cell. The SDR in grid cells is a strong function of the travel time of overland flow within the cell. The travel time is strongly dependent on the topographic and land cover characteristics of an area and therefore its relationship with the SDR is justified. The SDR is not homogeneous across a watershed. Instead it varies with changes in the topography and land use. According to Stefano *et al*. (2000), the SDR per cell indicates the probability that eroded particles mobilized from an individual cell will be transported to the nearest stream pixel and can be derived as follows:

$$SDR_i = \exp(-\beta \sum_{i=1}^{m} \frac{li}{a_i S_i^{0.5}}) \qquad (7)$$

where SDR_i is the sediment delivery ratio per cell, β is the watershed specific parameter, l_i is the flow length of the *ith* cell, a_i is the coefficient related to land use, and S is the slope of the *ith* cell (m/m).

If Y is the amount of soil erosion produced within the *ith* cell of the watershed

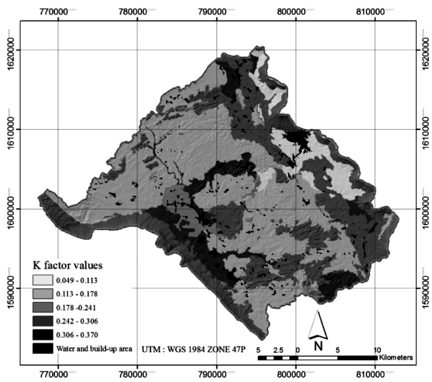

Figure 4. Spatial distribution of K factor in the study area

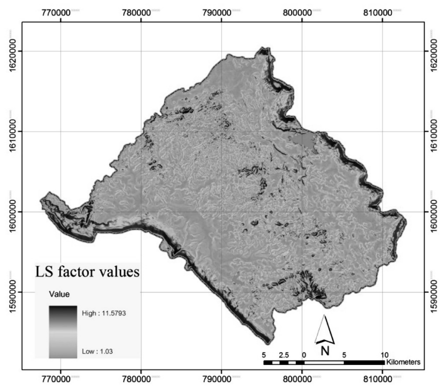

Figure 5. Spatial distribution of *LS* factor in the study area

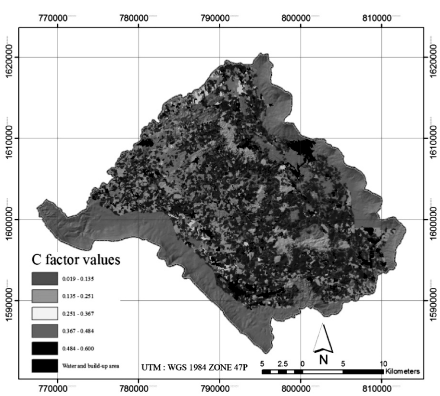

Figure 6. Spatial distribution of C factor in the study area

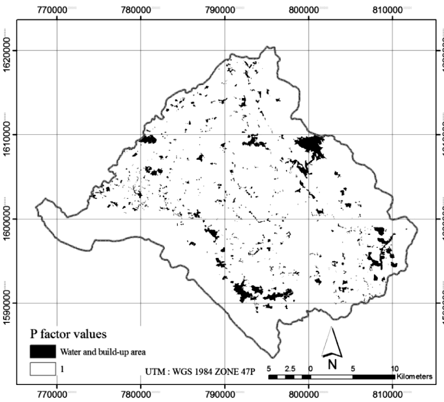

Figure 7. Spatial distribution of *P* factor in the study area

estimated using MUSLE, the sediment yield for the watershed, Sy, during a storm event was obtained as below:

$$S_y = \sum_{i=1}^{N} SDR_i \, Y \qquad (8)$$

where N is the total number of cells over the watershed and the term SDR_i is the fraction of Y_i that ultimately reached the nearest channel. Since the SDR_i of a cell is hypothesized as a function of travel time to the nearest channel, it implies that the gross erosion in that cell multiplied by the SDR_i value of the cell becomes the sediment yield contribution of that cell to the nearest stream channel. This hypothesis is accurate at the event scale only while it is applicable at the mean annual scale in other cases. The SDR spatial distribution is very important for identifying the critical sediment source and delivery areas as well as soil erosion control.

Tools Development

The tools were developed based on the grid-based operation of GIS processes. The computer program ModelBuilder™ of ArcGIS™ was used to create the model toolbox with a required set of spatial analyses. The runoff depth and sediment yield in each grid cell was computed using the SCS-CN method, MUSLE, and SEDD model, and then routed through the watershed based on flow direction and flow accumulation from 1 cell to the next until it reached the watershed outlet. The simulated runoff and sediment yield values were picked up from cells located at M.171 and M.145 stations. The outputs of the model simulation and observed values of all events at these 2 cells were tabulated to estimate the statistical indices for model evaluation.

Model Evaluation

The model evaluation procedure included calibration and validation. The runoff model used 10 and 8 rainfall events for calibration and validation, respectively, while the sediment yield model used 8 rainfall events for both. In each calibration step the simulation results of runoff and sediment yield were compared to the actual ones of selected events observed from the M.171 and M.145 gauge stations. The parameters 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 the model validation. The agreement between the simulation and observation results for selected events was assessed using 3 statistical indices which are the R^2, E, and percentage deviation (Dv).

The R^2 measures the linear dependence of observed and simulated values. The E (Nash and Sutcliff, 1970) is one of the indices most frequently used to assess hydrological models. It can be expressed as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} (Obs - Sim)^2}{\sum_{i=1}^{n} (Obs - \overline{Obs})^2} \qquad (9)$$

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 the forecast is not satisfactory: a long-term average of the observed quantity is better than the model outputs. In addition, Krause *et al.* (2005) noted that E is sensitive to the size of deviations of observed and simulated values for flood events with high discharge and sediment yield.

The percentage of deviation values, Dv, is given by the following equation:

$$Dv(\%) = \frac{Obs - Sim}{Obs} \times 100 \qquad (10)$$

where Obs is the observed value, and Sim is the simulated value. The closer this value is to *0* the better the model is. Dv would equal to *0* for a perfect model.

Results and Discussion

Runoff Estimation

The runoffs were estimated from different storm events during the monsoon period between June–October 2008. Results of the runoff model calibration and validation are displayed in Tables 1 and 2. Ten selected events were used for model calibration. Another 8 events were used for the model validation. The total runoff estimation or simulation of the 10 calibration events through stations M.171 and M.145 were 65.45 mm and 55.84 mm, respectively, while for the observations they were 68.94 mm and 46.79 mm, respectively. For the simulation of the 8 validation events at both stations, they were 33.62 mm and 32.02 mm, respectively, and for the observations they were 30.42 mm and 31.86 mm, respectively.

Runoff Model Calibration and Validation

A part of the calibration procedure for the runoff model was done by adjusting the "λ" values in Equation 3 in such a manner that the calculated E for all calibration events would be highest. The calibration results show that the model provides the best simulated results with E = 0.94, R^2 = 0.95 when adjusting λ = 0.1 for M.171 station and E = 0.87, R^2 = 0.91 when adjusting λ = 0.2 for M.145 station. The validation results show that E = 0.87 and R^2 = 0.89 for M.171 station and E = 0.68 and R^2 = 0.75 for M.145 station. The spatial variation of the event-based simulated runoff depths used for validation at M.171 and M.145 stations are displayed in Figures 8 and 9.

Comparison between observed and simulated runoffs for calibration and validation are shown in Figures 10 and 11,

Table 1. The results of runoff model calibration events

Calibration events	AMC	Runoff Depth (mm)							
		M.171 station				M.145 station			
		Rainfall (mm)	Q_{obs}	Q_{sim}	*Dv* (%)	Rainfall (mm)	Q_{obs}	Q_{sim}	*Dv* (%)
20080818	Dry	20.34	0.07	1.38	-1,851.78	20.35	0.45	1.46	-226.07
20080905	Dry	12.00	0.78	0.90	-15.81	10.56	0.94	2.86	-202.70
20080907	Normal	11.96	0.99	2.90	-193.07	5.50	0.80	1.22	-51.84
20080910	Wet	42.39	29.40	26.52	9.81	40.47	19.49	22.15	-13.63
20080915	Wet	16.69	10.52	6.88	34.61	13.49	3.70	3.64	1.81
20080918	Wet	18.89	7.44	8.96	-20.43	17.33	3.83	7.15	-86.40
20080930	Dry	21.82	5.77	2.93	49.18	26.08	4.79	3.48	27.29
20081003	Wet	16.42	6.51	6.45	0.84	15.42	5.76	4.32	25.07
20081018	Dry	8.89	0.96	0.62	34.79	6.53	0.67	3.81	-466.95
20081030	Normal	27.47	6.50	7.90	-21.45	28.66	6.34	5.76	9.16
Total			**68.94**	**65.45**			**46.79**		**55.84**
E				**0.94**					**0.87**
***R*²**				**0.95**					**0.91**
Average deviation (%)				**-197.33**					**-98.43**

respectively.

From the scatter plot of observed and simulated runoffs for calibration it is observable that, compared to the observed values at the M.171 station, the simulated values are slightly above the 1:1 line, indicating that the model has a slight underestimation. Meanwhile, compared to the observed values at the M.145 station, the simulated values are slightly below the 1:1 line, indicating that the model has a slight overestimation. It can be concluded that the comparison results at both the M.171 and M.145 stations, as shown in the scatter plot, are quite satisfactory.

From the comparison scatter plot of the observed and calibrated-simulated runoffs for validation, it is observable that at the M.171 station the model has a slight overestimation as the relation line is slightly below the 1:1 line. At the M.145 station the relation line is slightly below the 1:1 line when the runoff is approximately higher than 4.5 mm, indicating that the model has a slight overestimation in heavier events.

Sediment Yield Estimation

Results of the sediment yield estimation in terms of the model calibration and validation of both stations are shown in Tables 3 and 4. Eight selected events were used for the model calibration and another 8 events were used for the model validation. For the 8 calibration events, the total sediment yield estimation or simulation resulted in 51,011.08 metric tons, while it was 46,362.42 from the observations. For the 8 validation events, the total simulation was 15,864.56 metric tons, while it was 13,668.67 metric tons from the observations.

Sediment Yield Model Calibration and Validation

A part of the calibration procedure was done by adjusting the "β" values in Equation 7 in such a manner that the calculated E for all

Table 2. The results of runoff model validation events

Validation events	AMC	Runoff Depth (mm)							
		M.171 station				M.145 station			
		Rainfall (mm)	Q_{obs}	Q_{sim}	*Dv* (%)	Rainfall (mm)	Q_{obs}	Q_{sim}	*Dv* (%)
20080819	Dry	12.38	0.11	0.71	-550.90	13.74	1.19	2.58	-117.88
20080906	Dry	17.23	1.63	1.50	8.39	22.26	2.47	2.16	12.64
20080909	Normal	16.86	1.16	3.15	-170.94	15.93	1.53	1.59	-3.73
20080912	Wet	25.72	12.08	13.02	-7.74	28.36	10.80	12.87	-19.20
20080928	Dry	25.56	2.20	2.55	-15.78	27.18	1.59	1.81	-14.26
20081001	Normal	15.91	3.84	5.85	-52.55	17.97	3.55	5.44	-53.48
20081008	Normal	13.32	3.85	2.30	40.22	14.35	3.51	1.90	45.67
20081025	Dry	31.51	5.54	4.54	18.14	39.80	7.23	3.64	49.59
Total			**30.42**	**33.62**			**31.86**	**32.02**	
E				**0.87**				**0.68**	
R^2				**0.89**				**0.75**	
Average deviation (%)				**-91.40**				**-12.58**	

calibration events would be highest. The simulated sediment yields show that the model provides acceptable results with $E = 0.85$ and $R^2 = 0.89$ when adjusting $\beta = 0.2$ for calibration and $E = 0.79$ and $R^2 = 0.92$ for validation. Figure 12 shows the spatial variation of the simulated sediment yields from the validation events.

Comparison between the observed and simulated sediment yields for the calibration and validation events are shown in Figures 13 and 14, respectively.

The scatter plots of the observed and simulated sediment yield for the calibration show that the relation line is slightly above the 1:1 line when the sediment yield is

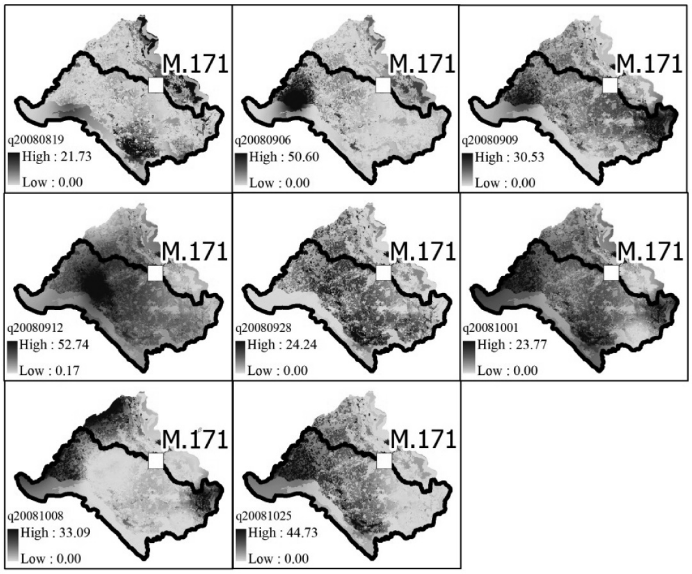

Figure 8. The spatial variation of event-based simulated runoff depths (mm) used for validation at the M.171 station

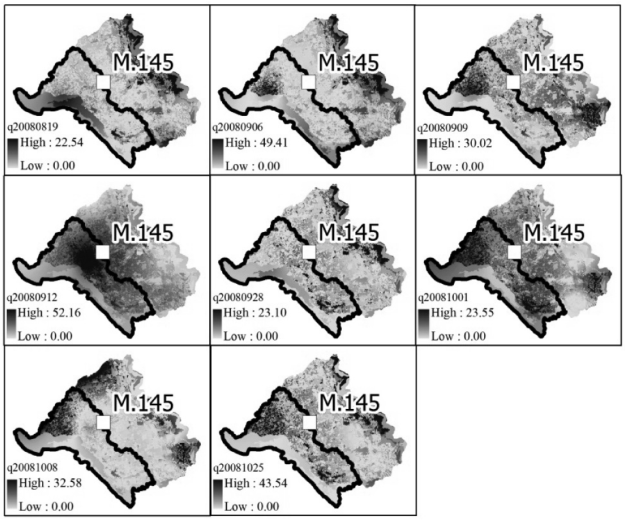

Figure 9. The spatial variation of event-based simulated runoff depths (mm) used for validation at the M.145 station

approximately higher than 8,000 metric tons, indicating that the model has a slight underestimation in heavier events. The number of events is too small and results in a not well distributed scatter plot.

From the scatter plots of the observed and calibrated-simulated sediment yield for the validation, it is observable that the relation line is below the 1:1 line when the sediment yield is approximately below 2500 metric tons. It indicates that the model has a slight overestimation in general events when the rainfall was around 10-25 mm. It also shows that for the uncommon heavier rainfall events the model can have more underestimation. In reality, the heavier events cause the erosion of the river stream banks which was ignored in this study. Normally, the larger runoff can cause stronger erosion and has a bigger sediment transport capacity and thus can deliver more sediment to the outlet. The error encountered in events observed at the M.171 and M.145 stations could be explained by the models really providing every cell simulation and accumulating them from upstream to the cells at the stations while the observations or actual processes were hardly able to exist in all cells. Plus, the observations or time-series manual samplings might not be able to conduct at the right time what can represent

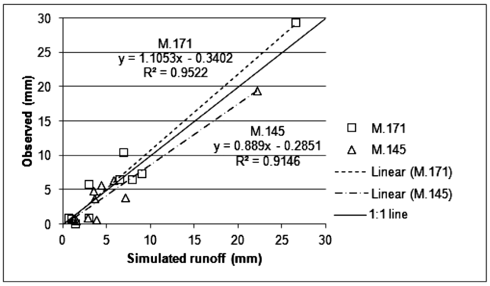

Figure 10. Comparison of observed and simulated runoffs for calibration

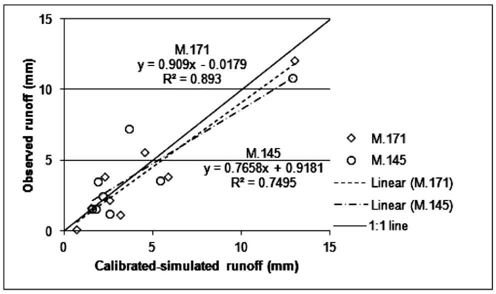

Figure 11. Comparison of observed and calibrated-simulated runoffs for validation

Table 3. The results of sediment yield in model calibration

Calibration events	AMC	Sediment yield (metric tons)		
		Observed (S_{Yobs})	Simulated (S_{Ysim})	*Dv* (%)
M171_20081030	Normal	564.06	6285.71	- 1014.35
M171_20080930	Dry	3143.87	1563.78	50.26
M171_20080818	Dry	149.17	406.55	- 172.54
M171_20080910	Wet	37797.98	28470.30	24.68
M145_20081030	Normal	308.19	2854.50	- 826.22
M145_20080930	Dry	1225.80	988.92	19.32
M145_20080818	Dry	166.54	135.92	18.39
M145_20080910	Wet	3006.80	10305.40	- 242.74
Total		**46362.42**	**51011.08**	
E			**0.85**	
R²			**0.89**	
Average deviation (%)			**- 267.90**	

the results of upstream activities at the stations, even though samples were collected at the instant times of expected peaks of the flow. This could be because rainfall, a dynamic variable, has too high spatial and temporal variations.

Conclusions

The integration of the SCS-CN method, MUSLE, SEDD method and geospatial modeling was implemented in a grid-based GIS that represents the distributed runoff and

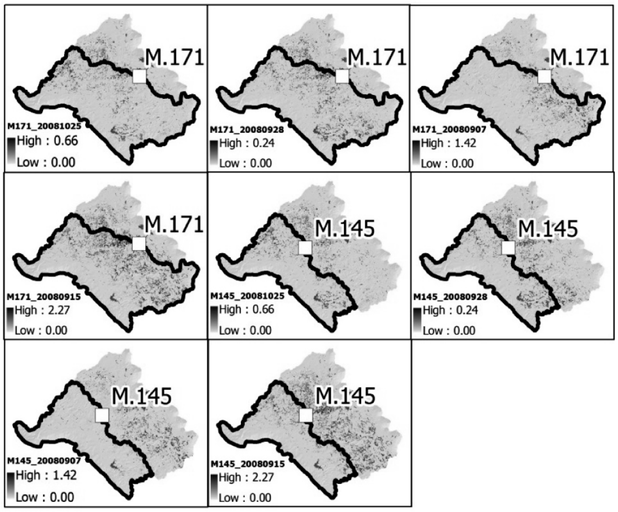

Figure 12. Spatial variation of event-based simulated sediment yields used for validation at the M.171 and M.145 stations

Table 4. The results of sediment yield in model validation

Validation events	AMC	Sediment yield (metric tons)		
		Observed (S_{Yobs})	Simulated (S_{Ysim})	*Dv* (%)
M171_20081025	Dry	579.39	2242.69	- 287.07
M171_20080928	Dry	196.02	1159.69	- 491.61
M171_20080907	Normal	1128.25	1803.25	- 59.83
M171_20080915	Wet	9883.82	6703.69	32.18
M145_20081025	Dry	423.81	1682.77	- 297.05
M145_20080928	Dry	98.99	592.35	- 498.37
M145_20080907	Normal	269.03	93.60	65.21
M145_20080915	Wet	1089.34	1586.53	- 45.64
Total		**13668.67**	**15864.56**	
E			**0.79**	
R^2			**0.92**	
Average deviation (%)			**- 197.77**	

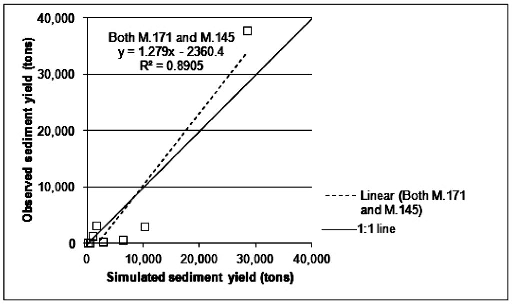

Figure 13. Comparison of observed and simulated sediment yield for calibration

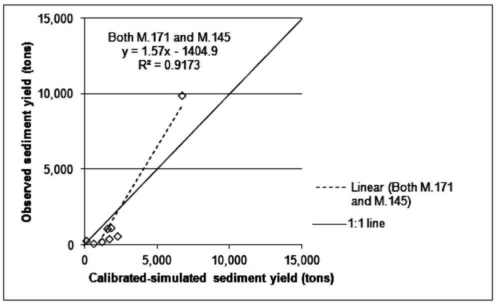

Figure 14. The comparison of observed and simulated sediment yield for validation events

sediment yield processes. Inclusion of the distributed spatial characteristics provided a significant advantage in the modeling compared with the lumped model.

The runoff process locally worked on spatial variation of features which are land use, HSG, rainfall, and topographic characteristics, leading to runoff potential assessment. As a result of the case study at the Upper Lam Phra Phloeng watershed, it can be confirmed that the grid-based modified SCS-CN method is applicable to surface runoff estimation and is effective.

The sediment yield estimation based on the MUSLE and SEDD model was implemented in a grid-based GIS as well. The yield in each grid cell was computed using the MUSLE and the route through the watershed based on the sediment delivery ratio using the SEDD model. The distributed processes were locally operated on the spatial variables, namely runoff depth, peak discharge, *K* factor, *LS* factor, *C* factor, *P* factor, flow length, and slope. The models can be applied to sediment yield simulations with acceptable accuracy. Not only were satisfactory results provided but the models are also able to estimate varying sediment yield over the watershed spatially. Although the bigger deviation of individual event-based simulation and observed data exist, for overall consideration, particularly the annual yield, accumulation of all events obtained using the models could be acceptable.

The performance of the models was obviously increased by the calibration processes. However, it is recommended that application of the models to a new study area with different geographical characteristics requires calibration of certain parameters for better accuracy.

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