RESEARCH ARTICLE
doi: 10.2306/scienceasia1513-1874.2011.37.043

Predicting sediment discharge in an agricultural watershed: A case study of the Lam Sonthi watershed, Thailand

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Received 30 Sep 2009
Accepted 8 Feb 2011

ABSTRACT: The purpose of this study was to simulate the processes of sediment discharge in Lam Sonthi agricultural watershed in central Thailand using a soil and water assessment tool (SWAT) model. The SWAT model was calibrated and validated using input data collected during 1997–2002. The results showed that the values of both the correlation coefficient and Nash-Sutcliffe coefficient were above 0.70. Simulated sediment discharge was found to be lower than originally estimated for some months, particularly during seasons prone to flooding, but most of the predicted values were close to those graphically and statistically observed. Although the model was evaluated using only limited data and some of the algorithms used were not entirely appropriate for the tropical conditions found in the watershed, overall the results were within acceptable levels for estimating monthly sediment discharge. This led to the conclusion that the SWAT model can reliably predict monthly sediment discharge for any agricultural watershed which has conditions similar to those of the study watershed.

KEYWORDS: soil erosion model, calibration, soil and water assessment tool (SWAT)

INTRODUCTION

Water-based soil erosion and soil sedimentation are two of the most serious environmental problems facing the world today and through this many landscapes across the globe have been adversely affected. While soils have always been subject to erosion by forces of nature, such as water, wind, and ice, the process has been greatly accelerated by human activities such as deforestation, agricultural expansion, and construction. These have increased the rate of erosion from two to 40 000 fold[1]. Consequently, huge amounts of upland soil and sediment are displaced and transported down to lowland areas and into water bodies downstream, causing sedimentation.

The process of soil erosion takes place as a result of a complex interaction between several factors, including climate patterns, topography, soil properties, and land use/cover. As the process is dominated by natural variability, predicting sedimentation rates is a challenging task. In the past, soil erosion was mostly studied on a plot-scale, whereby a number of long-term experiments were conducted to determine the relationship between soil erosion and pertaining factors such as climate, soil types, crops, and topography. Such experiments were often expensive to conduct and required vast human resources. However, in recent years soil erosion and transported sediment have been predicted using erosion models that simulate the processes of soil erosion, land management, and soil conservation without the need for time-consuming and costly experiments. Erosion models have increasingly been attributed to the fast growth of both geographic information systems (GISs) and computer technology and a number of models have been applied to investigate erosion problems in various regions around the world. AGNPS[2], ANSWER[3], EUROSEM[4], LISEM[5], SWAT[6], and other such models have been used to simulate not only sediment discharge but also water quality problems in a number of watersheds.

One of the most commonly used erosion models is the Soil and Water Assessment Tool (SWAT) is a public domain watershed scale model developed to predict the effects of land management on water, sediment, nutrients, pesticides, and agricultural chemicals in small to large complex basins[7]. It is a physically based, semi-distributed parameter model with a robust hydrologic and pollution model that has been successfully employed in a number of watersheds. SWAT has been applied in a number of watersheds. Most previous studies focused on streamflow predictions, with average monthly streamflows being used mostly to calibrate and validate the model[8–11]. Applications of SWAT have expanded worldwide over the past decade, especially in the US and Europe[12], but there is still a paucity of SWAT research on predicting sediment discharge in tropical countries like Thailand. This may be due to the lack of temporal and spatial scale data used for modelling watershed hydrology and sediment in tropical regions.

Accurately assessing the process of sedimentation in Thailand is a very important task because land in many parts of the country is mountainous and subject to large amounts of rainfall and high rainfall intensity typical of tropical regions. Moreover, the forested areas are decreasing and agricultural activities are causing serious soil erosion. Consequently, a clear understanding of soil erosion and the ability to accurately predict the erosion processes are essential for appropriate watershed management. As SWAT is a semi-distribution watershed model, the relevant model's parameters need to be calibrated to suit the conditions of the watershed being studied. The aim of this study is to evaluate the ability of the SWAT model to correctly analyse and predict sediment discharges using environmental conditions typical to Thailand.

METHOD

Study watershed

The Lam Sonthi river watershed, a sub-basin of the Pasak Basin, was selected for this study because nearly every year the watershed experiences flash floods and landslides. Agricultural areas within the watershed have expanded rapidly in recent years, decreasing the soil's ability to store water and also greatly reducing areas of forest that protect soil from the erosive effects of rain and subsequent runoff.

During the wet season, huge volumes of water and soil particles are quickly routed downstream. In 2001 and 2002 floods devastated Nam Koa and Muang Phetchabun districts, resulting in a great loss of life, injury, disease, and damage to property.

The Lam Sonthi River Watershed (357 km^2) is located between the north and central plains of Thailand (Fig. 1). The topography is mountainous with steep slopes running along both sides of the watershed, while the middle and lower portions of the watershed are quite flat. The altitude varies from approximately 100–700 m.

In the study area, the climate is tropical, with the wet season running from May to October and the dry season from November to April. The mean annual precipitation of the area is 1134 mm and the mean annual temperature ranges between 19.2 and 35.8 °C. The average wind speed is 2.12 km per hour, with strong winds always occurring during the wet season. Maximum/minimum daily evaporation is 10.94 mm per day in April and 0.34 mm per day in June.

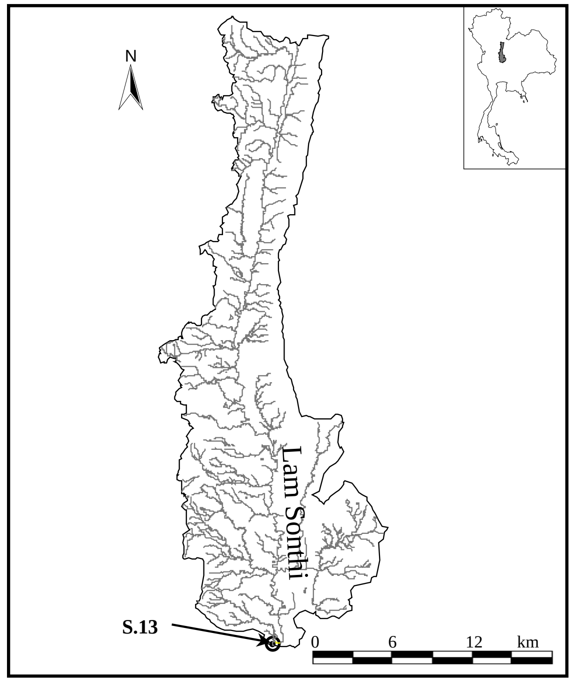

Fig. 1 Study area: Lam Sonthi river watershed, Thailand.

Types of land use in the watershed include agriculture, forest cover, villages, and bodies of water. Agriculture accounts for 40% of land use in the area, with maize, fruit trees, and rice being the most commonly grown crops. Forest covers approximately 59% of the watershed with dense forest comprising 30% and deciduous forest 29%. The remaining 1% of land is made up of villages and bodies of water.

Like many other watersheds in developing countries, the quantity and quality of data available for use in this kind of study is scant. SWAT requires an extensive amount of data all of which are in short supply for the Lam Sonthi River Basin. Meteorology data was devoid of information on wind speed, solar radiation and relative humidity. Similarly, only time-series data on temperature was available for modelling evapotranspiration (ET), while information on water supplied by a small irrigation system within the area to irrigate fields was also unavailable.

SWAT model description

The major components of SWAT are climate, hydrology, erosion, land cover/plant growth, nutrients, pesticides, and land management[7]. The SWAT was used to simulate the hydrologic processes of the study watershed. The processes are calculated based on the water balance equation:

$$S_t = S_0 + \sum_{i=1}^{t} (R - Q_{\mathrm{surf}} - E_{\mathrm{a}} - w_{\mathrm{seep}} - Q_{\mathrm{gw}})$$

where S_t is the final soil water content (measured as a height), S_0 is the initial soil water content, t is the time in days. R is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_{a} is the amount of evapotranspiration on day i, w_{seep} is the amount of percolation and bypass flow exiting the soil profile bottom on day i, and Q_{gw} is the amount of return flow/base flow on day i.

Surface runoff volume is calculated by using a modification of the SCS curve number approach. Peak runoff is computed by a modification of the rational method. Runoff routing in the channel is estimated by the Muskingum routing method. SWAT offers three options for estimating potential evapotranspiration (PET): Penman-Monteith, Priestley-Taylor, and Hargreaves. The model calculates the amount of percolation and bypass flow through the soil layers by using a storage routing technique. The shallow aquifer means an unconfined aquifer that contributes to flow to the main channel or river reach in the sub-watershed. The deep aquifer is a confined aquifer and the entering water is assumed to contribute to streamflow somewhere outside the watershed.

The model calculates evaporation from soils and plants separately. Potential soil water evaporation is computed as a function of the PET and leaf area index. Actual soil water evaporation is calculated using the exponential functions of soil depth and water content, while plant water evaporation is estimated as a linear function of the PET, leaf area index, root depth (from crop growth model), and soil water content.

The SWAT model uses a simplification of the EPIC crop model. A single model is used for simulating both annual and perennial plants. The crop growth from planting concepts is based on daily-accumulated heat units, the harvest index for partitioning grain yield for potential biomass, and water and temperature stress adjustments. The canopy cover and the root development are estimated as a function of heat units and crop biomass.

Soil erosion in SWAT is calculated using a modified version of the USLE[13] model, called MUSLE[14]. This model was modified by replacing the rainfall factor used in USLE with a runoff factor (for both volume and peak flow). Sediment in SWAT is calculated using

$$\mathrm{sed} = 11.8\,(Q_{\mathrm{surf}} q_{\mathrm{peak}} A_{\mathrm{hru}})^{0.56}\, KCP\, \mathrm{LS}\, \mathrm{CFRG}$$

where sed is the sediment yield on a given day (t), Q_{surf} is the surface runoff volume (mm/ha), q_{peak} is the peak runoff rate (m^3/s), A_{hru} is the area of HRU (ha), K is the soil erodibility factor (0.013), C is the land cover and management factor, P is the support practice factor, LS is the topographic factor, and CFRG is the coarse fragment factor.

The sediment routing model consists of both deposition and degradation components which are operated simultaneously. The deposition process is based on fall velocity and the degradation process is a modification by Williams[15] of Bagnold's stream power concept. Fall velocity is estimated as a function of particle diameter squared using Stoke's Law. Excess stream power produces bed degradation that is adjusted by USLE soil erodibility and the cover factor of the channel and flood plain. A full explanation of SWAT theories and structure is given in Ref. 7.

Model building

SWAT requires extensive data on meteorology, topography, land use, soil series, and land management. Meteorological data employed in this study was acquired from the Thai Meteorological Department and the Royal Irrigation Department (RID). Hydrologic time-series data including runoff across the entire study area was acquired from the RID. Information on soil and land use was obtained from the Land Development Department (LDD). Topographical maps at scales of 1:50 000 were procured from the Royal Thai Survey Department (RTSD). Planting and harvest dates for crops were obtained from a local agent (the provincial agricultural office). Harvesting of maize was from May to August for the first crop and from December to March for the second crop. For seasonal rice, the growing period starts in May and harvest occurs within the next four months (August). The second crop of rice is grown from early September to December.

Daily precipitation and temperature data for 1997–2002 were reformatted into database files and prepared for use as SWAT input files. The observed sediment discharges were then compared with the simulated results for the calibration and validation procedures. Contours were added, at 20-m intervals, to elevations based on the 1:50 000 scale topographical map, using Geographical Information Systems software. A digital elevation model (DEM) then derived the topographic data as slope, aspect, flow direction, and flow network. The study area was delineated into 27 sub-basins based on surface topography provided by the DEM, and the parameters of each of these were calculated using SWAT.

Digital land use data (LDD database) was processed and reclassified to match the SWAT model land use code. Ten different categories of land use in the study area were used for SWAT processing. The data were also used for future sub-classification of land in the watershed. Fourteen types of soil were found in the study area. The data were then converted and reclassified to match the SWAT formats in order to support the model's requirements.

The initial curve number values were assigned based on the land use type and soil hydrologic group for the average antecedent moisture condition of the curve number method. The PET was computed by using Hargreaves' method because only temperature data were available. A dominant soil and land use type within each sub-watershed was used to develop soil and plant inputs to the SWAT model. Several kinds of crops such as maize, fruit trees, and rice were assigned as vegetation input. The planting and harvest dates for these crops were also scheduled and used to build the SWAT management input file.

Model calibration procedures

A traditional split-sample technique was conducted against observed sediments of a watershed outlet gauging station (S.13). The sediment module of SWAT was calibrated and validated using daily data collated between 1997 and 2002. The model was 'warmed up' using data from 1995 through 1996 after which data from the next six years were used for calibration and validation. The predicted monthly sediment data were compared with the monitored values to evaluate the performance of the SWAT model.

The relevant model parameters were manually adjusted during the calibration period to within the range suggested by Neitsch et al[7] and until the predicted monthly sediment discharge was reasonably in line with that which had been observed. For sediment components, the relevant variables including peak rate adjustment factor for sediment routing in sub-basin (ADJ_PRK) and for sediment routing in the channel (PRF), land cover and management factor (USLE_C), soil erodibility factor (USLE_K), practice factor (USLE_P), coefficient in sediment transport equation (SPCON), exponent in sediment transport equation (SPEXP), and channel erodibility (CH_EROD) were fine-tuned.

Evaluation of model performance

The evaluation of the model was carried out to determine whether the model can accurately represent the physical processes occurring in a watershed. At present, statistical methods are the most commonly used form of evaluation and there are numerous statistical analysis methods available for evaluating the results of a model simulation. We used the correlation coefficient (R) and Nash-Sutcliffe coefficient (E_{NS})[17]:

$$E_{\mathrm{NS}} = 1 - \frac{\sum (Q - Q_{\mathrm{sim}})^2}{\sum (Q - \langle Q \rangle)^2}$$

where Q is the measured monthly discharge, Q_{sim} is the computed monthly discharge, and $\langle Q \rangle$ is the average measured discharge.

In this study, predicted monthly sediment discharges were calibrated to match observed monthly sediment discharges at the watershed outlet station and were deemed satisfactory if $R^2 > 0.6$ and $E_{\mathrm{NS}} > 0.5$, as recommended in Ref. 18.

RESULTS AND DISCUSSION

Summary of flow evaluation

The hydrologic module of the SWAT for the study watershed was calibrated and validated by Phomcha et al[19] using the daily input data from 1997–2002 and the model was graphically and statistically evaluated. Monthly observed and simulated flows were used to evaluate the performance of SWAT in the study watershed. The results indicated that the average monthly ET values were estimated as 38.2 and 79.8 mm for dry and wet months, respectively. These simulated values were acceptable when compared to previous studies on ET for this region[20,21]. Both R^2 and E_{NS} were above 0.70. The deviation for the runoff volume (D_{v}) was also acceptably accurate. Although some months of simulated flow were overestimated, particularly during annual dry seasons, most simulated flow was both graphically and statistically close to the observed flow (Fig. 2). A complete detailed description of streamflow simulation in the study watershed is given in Ref. 19.

Sediment calibration and validation

Model parameters were adjusted until optimal predicted sediment outputs at the S.13 station in the study watershed were obtained for the period. The peak rate adjustment factor for sediment routing in sub-basin (ADJ_PRK) and for sediment routine in the main channel (PRF), and the exponential factor for the stream power equation (SPEXP) were fixed

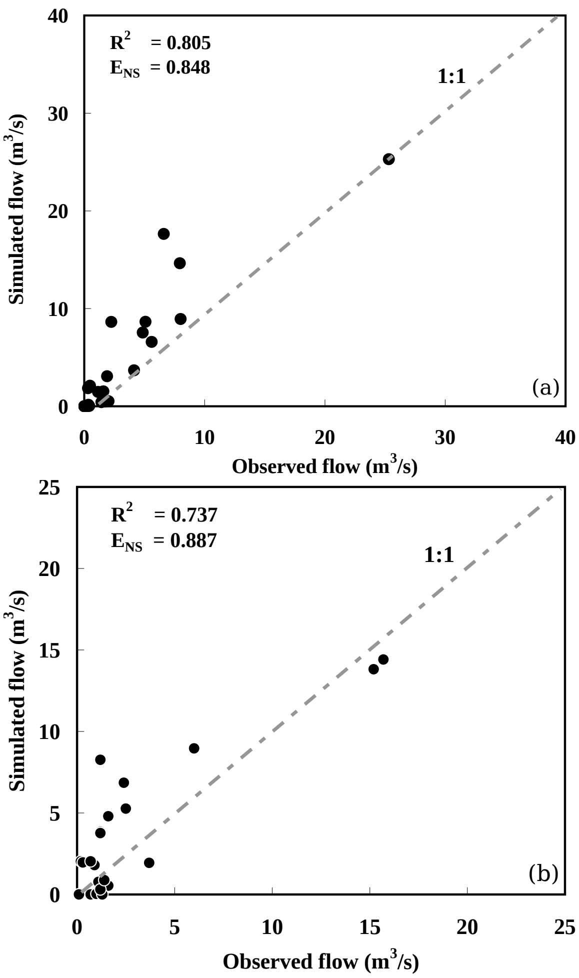

Fig. 2 Scatter plots of flow model (a) calibration and (b) validation.

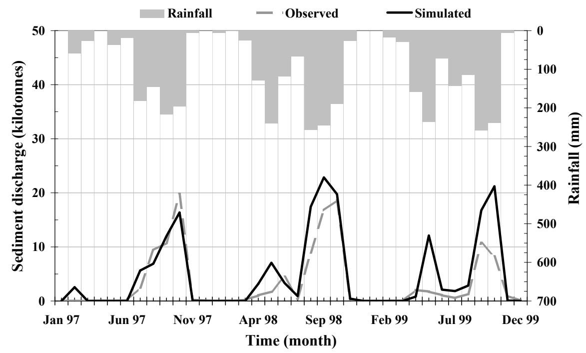

Fig. 3 Graph showing rates of simulated and observed monthly sediment discharge at watershed outlet for model calibration.

Table 1 The observed and simulated monthly sediment discharge for model calibration and validation.

Sediment discharge	Calibration (1997–1999)		Validation (2000–2002)	
	Observed	Simulated	Observed	Simulated
Average (t)	3398	4894	6706	4807
Max. peak (t)	19811	22860	141000	32550
Volume (10^3 t)	122	176	241	173

at 1.0. The coefficient in the sediment transport equation (SPCON) was adjusted to 0.0001. The channel erodibility factor CH_EROD was set to a higher value of 0.4. The land cover and management factor (USLE_C) for deciduous and evergreen forests were adjusted to 0.001, while all agriculture areas were changed to 0.5. The soil erodibility factor (USLE_K) of each soil series ranged between 0.11 and 0.27. The support practice factor (USLE_P) remained set at 1.0 for all land cover due to the fact that there is no soil conservation in the watershed.

Monthly sediment discharge at the watershed outlet were used as the observed values and plotted against the predicted values during the calibration and validation period (Fig. 3, 4, and 5). Table 1 shows the observed and simulated monthly sediment discharge for both calibration and validation. During the calibration period, model simulated sediment discharges matched those observed with a moderate degree of accuracy (Fig. 3). There was a 44% difference between the average observed and average predicted monthly sediment discharge throughout the period. Simulated sediment discharge was grossly overestimated for 1999, but reasonably well predicted for 1997 and 1998. Predicted peak sediment discharge quite closely matched the values observed in 1997 and 1998, differing by 17% and 6%, respectively. However, peak discharge was overestimated by some 56% for 1999. Simulated monthly sediment discharge from the SWAT model gave $R^2 = 0.78$ and $E_{\mathrm{NS}} = 0.79$. The scatter plot for model calibration (Fig. 4a) shows a uniform scatter of points above and below the 1:1 line for lower and higher rates of sediment discharge, but generally higher rates were plotted above the 1:1 line. This indicates that the model is inclined to overpredict rates of sediment discharge for the calibration period.

During the validation period, the predicted peak sediment discharge value as well as times-to-peak quite closely matched the observed values, when the large discrepancy for the year 2000 were omitted (Fig. 5). The predicted peak sediment discharge for 2001 differed by just 1%, while for 2002 the value was underestimated by 37%. However, the most pronounced underestimation was 77% for year 2000.

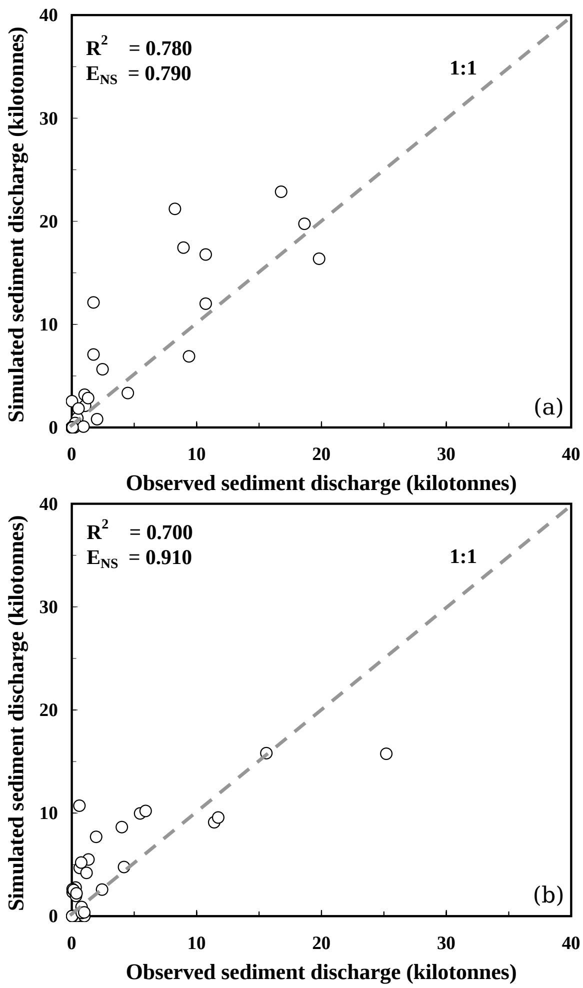

Fig. 4 Scatter plots of sediment model (a) calibration and (b) validation.

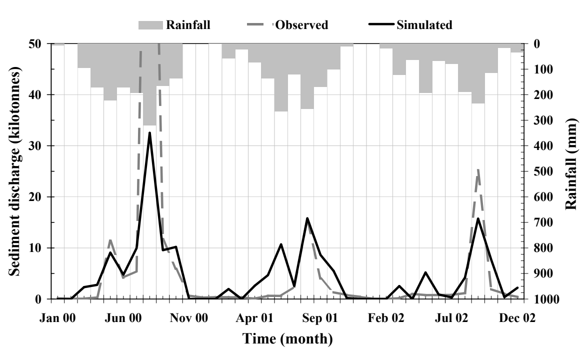

Fig. 5 Graph showing rates of simulated and observed monthly sediment discharge at watershed outlet for model validation (excluding the maximum observed sediment discharge in August 2000).

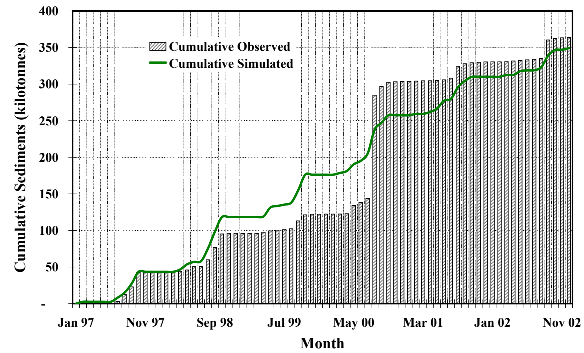

Fig. 6 Cumulative simulated sediments against observed sediments at watershed outlet.

Simulated sediment discharge reasonably matched that observed for the values of R^2 (0.69) and high values of E_{NS} (0.92). Scatter plots showing both observed and simulated rates of discharge are presented in Fig. 4b. Most of the points were evenly distributed above the 1:1 line (lower values), whereas some were plotted below (higher values). The diagram indicates that the model slightly over-predicts sediment discharge for lower sediment values, while it under-predicted the level for higher sediment values over the course of the validation period.

Although the model both under-predicted and over-predicted sediment volume throughout the calibration and validation period, Fig. 6 shows that there is a strong correlation between the cumulative simulated and observed sediment throughout the 6-year evaluation period. This suggests that for long-term simulations, sediment volumes would be satisfactorily predicted by the model. However, the marked under-prediction of sediment in August 2000 is unacceptable and attempts to adjust sediment variables could not improve the prediction. Similar simulation results have also been reported in several other studies on the SWAT model[18,22,23]. In this study, one possible reason may be the lack of some input dataset in the watershed, such as information on pertinent water use by small irrigation projects (both pumped and diverted directly from streams) which was unavailable. As a result, the low quality of the dataset may have contributed to the shortcomings experienced in predicting sediment discharge. Another possible cause may result from errors incurred when one model component propagated into another. SWAT calculates sediment discharge using the output from the hydrologic module, thus the shortcoming for the estimated streamflow can be aggregated into the sediment module. For example, during the calibration period the over-prediction of levels of sediment discharge in 1998 and 1999 were over-estimated at similar levels by which the model over-predicted streamflow [19]. This is because the sediment component of SWAT uses the surface runoff volume and peak flow from the hydrologic module to compute the volume of sediment. The use of oversimplified SWAT algorithms to calculate both upland and in-stream erosion sediment is a third possible reason for discrepancies in this study. The largest volume of sediment (almost 150 kt) was recorded in the month of August 2000 as a result of the largest flood ever recorded in the study watershed. The SWAT model uses many empirical and quasi-physically-based algorithms in determining sediment component, including upland erosion and in-stream sediment transport.

For upland erosion, MUSLE was modified by replacing the rainfall factor of USLE with the runoff factor to simulate soil loss on sub-watersheds. MUSLE tended to over-predict sediment yields for small events and under-predict sediment yields for large events [24, 25]. This weakness might be one of the major causes of the high level of under-prediction of the sediment yield by the SWAT model, as the study watershed is located within a tropical climate, whereas MUSLE was developed using hydrological data from throughout the US. Tropical rain storms are nearly always more intense than those in temperate climate [26, 27]. Consequently, the intense rainfall that accompanies heavy storms has the potential to erode as much surface soil in the watershed as the subsequent runoff, but MUSLE does not account for such factors.

For in-stream sediment transport, shortcomings during the flood period might be attributed to the oversimplified assumptions made by SWAT. Arnold et al [6] noted that SWAT sediment routing equations are relatively simplistic. The SWAT simplifies Bagnold's concept to defining the maximum amount of sediment that can be transported from a reach segment as the function of the peak channel velocity. However, this concept is relatively crude as sediment transport characteristics such as bottom shear stress are not taken into account in the current version of SWAT [22]. The high shear stress within the high streamflow can scour both the stream bank and bed, greatly increasing the amount of sediment particles in the streamflow [28], particularly during flood seasons. This oversimplified concept of sediment calculation must also be considered when examining discrepancies in sediment discharge because degradation of the stream bank and bed are not adequately incorporated by the model.

Even though the SWAT model has some limitations for predicting rates of sediment discharge in the study watershed, the overall results were within the criteria range of this study. SWAT is based on a number of empirical and quasi-physical algorithms, such as SCS curve number, ground water flow, MUSLE, and sediment transport, which might not be appropriate for tropical climates. Consequently, such simple concepts should be modified to suit the environmental conditions of this region in order to improve predictions made by the model.

As a result of the large discrepancy in predicted sediment discharge, this study suggests that future studies of the upland erosion equation and in-stream sediment components using SWAT should be thoroughly examined and modified to better understand the processes that occur in tropical conditions. Also, guidelines for the planning and management of soil erosion in the watershed, based upon severe levels, are necessary for future work.

Acknowledgements: The authors would like to thank the officers of the LDD, RID, and RTSD for supplying the original data used in this study and also the reviewers for their valuable comments.

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