The Estimation of Sediment Dynamics in Mae Chaem River Basin Using SWAT Model

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Abstract

Natural erosion and deposition of sediment along the Mae Chaem River bank area caused by the fluctuated stream flowing through channel segments. The effect of rainfall on soil particles, particularly during the rainy season, causes the soil surface to be washed and moved down the river. Furthermore, sediment transport can destabilize river banks and have an impact on ecosystems, people' livelihoods, and land use management along riversides. As a result, the objective of this study is to assess the daily flow and sediment transport of the Mae Chaem Basin from 2004 to 2013 using the Soil Water Assessment Tool (SWAT) model. Furthermore, utilizing the Sequential Uncertainty Fitting 2 (SUFI-2) technique, the SWAT-CUP program was used to emphasize the sensitivity of parameters in a hydrological model. The discharge of model results was calibrated using station 061302 as the inlet and stations P.14 and P.14A as the outlets, with stations 061302 and P.14 also serving as sediment measuring stations. The statistical values of the Coefficient of determination (R^2) and the Nash–Sutcliffe model efficiency coefficient (NSE) were in range of 0.89 to 0.46 for calibration and validation periods of sediment evaluation. Furthermore, sediment load simulation revealed that the majority of sediment deposition occurred in the middle of Mae Chaem District, whereas bank erosion was intensely formed downstream, covering the area of Kong Khaek Sub-district, Mae Chaem District, and Bo Luang Sub-district, Hot District, Chiang Mai province.

Keywords: SWAT, SWAT-CUP, Sediment Evaluation, Mae Chaem River Basin

1. Introduction

River bank erosion is a common natural disaster along rivers in Thailand. Due to the variability of natural currents with seasonal precipitation and flow rates, estimating sediment yields and the dynamics of sediment displacement are costly and complex tasks. The hydrological model as the Soil Water Assessment Tool (SWAT) is utilized for estimating runoff volumes and predicting the impact of land management in the Mae Chaem Basin. Additionally, the SWAT model was properly established to forecast the water and sediment cycle in order to governing the mitigation plan for bank erosion; [1]. In the SWAT model, there are several variables involved in effecting the discharge and sediment evaluations, sorted by cluster of soil, groundwater, river characteristics, and weather variables. Furthermore, the sensitivity of SWAT parameters requires dynamic modification of parameters during the simulation. The sensitivity of SWAT parameters required for dynamic modification of parameters during the simulation. Therefore, the Sequential Uncertainty Fitting 2 (SUFI-2) in SWAT-CUP program was designed to assess the sensitivity and uncertainty of the indigenous SWAT models; [2].

However, most sediment flow assessments did not identify and characterize the displacement of suspended sediments along rivers. The SWAT model is a hydrological model that can identify and assess preliminary ranges in the riverbed where deposition and degradation occur at the river banks. Therefore, this study focused on: (1) evaluating the discharge and sediment flow in the Mae Chaem River using the SWAT model to identify the dynamic of suspended sediments along the Mae Chaem River banks, (2) determining the sensitivity parameters of discharge and sediment transportation.

2. Study Area and Materials

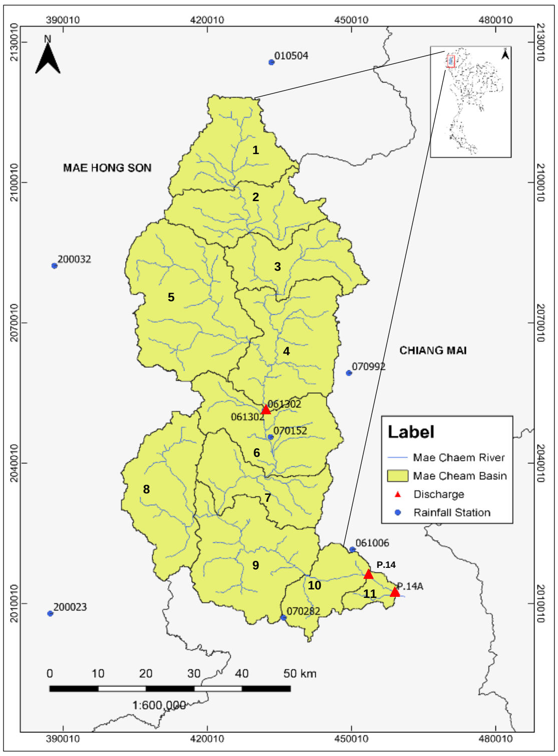

Fig. 1 Study area, Rainfall station and Discharge Gages

The Mae Chaem River Basin is an important tributary of the Ping River Basin, which is the main watershed in the upper northern part of Thailand. 90% of the main land of the watershed is located in Mae Chaem District, Chiang Mai Province, and the southwest of the basin, covering the area of Mae La Noi District, Mae Hong Son Province. There are also some areas on the southern side of the basin, located in the areas of Hot District and Chom Thong District, Chiang Mai. The river is located at an average height of above 760 M.S.L., with its headwaters at Doi Kiew Pa Kang, Ban Chan Subdistrict. The downstream of the river ends at Ban Sop Chaem, Hot Hod District. The Bain has an area of approximately 3,927 km2 with a total length of 170 km. The Mae Chaem Basin is a mountainous watershed that spans latitudes ranging from 18°12′N to 19°8′N and longitudes ranging from 98°8′E to 98°34′E; [3]. The annual average rainfall is 970 mm, with approximate annual maximum and minimum temperatures of 24 °C and 14 °C, respectively.

2.1 SWAT Model

The Soil and Water Assessment Tool (SWAT) is semi-distributed model that was developed to simulated rainfall-runoff, evapotranspiration, subsurface flow and the other hydrological response. Furthermore, the impact of change in weather, soil conditions and canopy interception were also allowed to predict in SWAT model from small to large scale. The model was expanded to coincide with physical movement of water and sediment, nutrient cycling, diffuse pollution, crop growth by importing input data; [4].

2.2 Principles the SWAT model Calculation

The SWAT declinate the watershed into subbasin the sub-divided due to the drainage area and the Hydrological Response Units (HRUs) which is the smallest spatial unit in SWAT model.; [5]. There are four elements entering through model manually, consist of the digital elevation, soil map, land cover and land use, and weather data of particular catchment. Similarly, the SWAT model used the water balance equation drive every process in particular watershed as shown in Eq.1

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

where SW_t is the final soil water content (mm), SW_o is the initial soil water content (mm), R_{day} is the precipitation (mm) Q_{surf} is the surface runoff (mm), E_a is the evapotranspiration (mm), W_{seep} is the water entering the vadose from the soil profile on day (mm), Q_{gw} is the return flow on day (mm)

2.2.1 The SCS Curve Number (SCS-CN) method

SCS-method was used for determining the amount of runoff from a rainfall event as show in Eq.2; [5].

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \quad (2)$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), I_a is the initial abstractions which includes surface storage, interception and infiltration (mm), and S is the retention parameter (mm)

2.2.2 Sediment Routing Equation

The Modified Universal Soil Loss Equation (MULSE) was used to evaluated the erosion and sediment yield as shown in Eq.3. Furthermore, the stream power, channel slope and peak channel velocity were consumed to determine the degradation and deposition in channel segments using the Bagnold's equation as show in Eq.4.; [6]

$$sed = 11.8\,(Q_{surf} \times q_{peak} \times area_{hru})^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG \quad (3)$$

where sed is the sediment yield (metric tons), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of HRU (ha), K_{USLE} is the soil erodibility factor, C_{USLE} is the cover and management, P_{USLE} is the support practice factor, LS_{USLE} is topographic factor and $CFRG$ is the coarse fragment factor

$$q = c \times (\rho/g) \times \sqrt{(d/D)} \times u_*^3 \quad (4)$$

where q is the mass transport of sediment, c is a dimensionless constant of order unity that depends on the sediment sorting, g is the local gravitational acceleration (m/s^2), d is the reference grain size for the sand (mm), D is the nearly uniform grain size and u_* is the friction velocity proportion.

The maximum of sediment that can be transported from a reach segment is calculated by Eq. 5; [7]

$$conc_{sed,ch,mx} = c_{sp} \times v_{ch,pk}^{spexp} \quad (5)$$

where $con_{sed,\,ch,\,mx}$ is sediment transportation loads ($tons/m^3$), c_{sp} is a coefficient defined by the users, $v_{ch,\,pk}$ is the peak channel velocity (m/s), and $spexp$ is an exponent defined by the users. If $con_{sed,\,ch,\,i} > con_{sed,\,ch,\,mx}$, deposition is the dominant process, on the other hand, if $con_{sed,\,ch,\,i} > con_{sed,\,ch,\,mx}$, the degradation is the dominant process in the reach segments

2.3 Sequential Uncertainty Fitting 2 (SUFI-2)

The SUFI-2 in SWAT-CUP program was severed for calibration and analysis the uncertainty of involving variables. The program determines the sequential and fitting values through the framework analysis accounting for the model input, conceptual model, model parameters and observed data (rainfall, discharge and sediment loads) during the stochastic calibration process; [8]. A Latin Hypercube Sampling was carried out to be an optimization approach, examining the behavior of objective function that was assigned before the simulation. The maximum and minimum optimal ranges of parameters was the constraints functions for sensitivity analysis. The initial parameters were narrowly modified at each iteration until satisfy the uncertainty criteria using the Jacobian and Hessian matric method. The optimal value of variables was generated at 95% probability distribution of the observed data which is called 95PPU. The 95PPU values were calculated at 2.5% and 97.5% of cumulative distribution of output variables.

3. Methodology

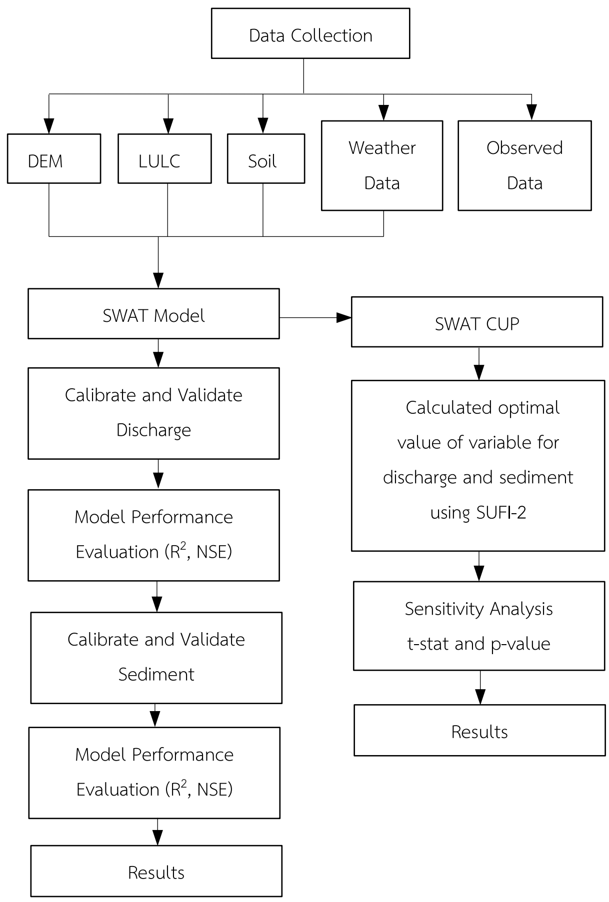

Fig. 2 The flowchart and conceptual model analysis in this study

3.1 Data Collection

- Digital Elevation (DEM): Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global
- Land Use and Soil Map: Land Development Department of Thailand (LDD)
- Weather Data (daily rainfall, temperature, humidity): Royal Irrigation Department of Thailand (RID), Department of Water Resource of Thailand (DWR), Meteorological Department of Thailand (TMD)
- Daily discharge and sediment measurement: Royal Irrigation Department of Thailand (RID) Department of Water Resource of Thailand (DWR)

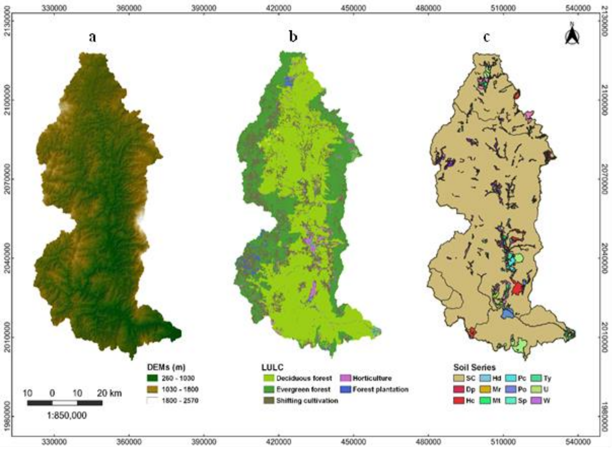

Fig 3. The secondary data for Mae Chaem River Basin; (a) Digital Elevation and River Stream; (b) Land use and Land cover; (c) Soil type

3.2 Calibration and Validation Model

In this study, the watershed was divided into 11 subbasins during the watershed delineation step. Furthermore, the multiple HURs were used to segregate the 5% for slope, soil, and LULC in order to increase model performance and neglect insignificant HRUs in each subbasin. The Muskingum Method was accounted for in routing the channel to perform the outflow and water yield. After the runoff model is accepted by statical value, the steam power will urge the gross erosion with USLE. The MUSLE equation will start routing and evaluating the daily sediment load. The discharge and sediment calibration were completed from 2004 to 2006, whereas the sediment calibration at station 061302 was initiated from 2007 to 2009 because of the data limitation. The validation years were selected based on the data availability. Therefore, the SWAT-model was validated from 2007 to 2013 for daily runoff and the sediment flow was validated during 2010 to 2013.

3.3 Parameterization analysis

The Sequential analysis of model parameters was divided into variables of flow rate and sludge yield. In addition, the process of selecting parameters and setting initial calibration intervals were stated for the parameterization in SWAT-CUP program. Based on the literature on SWAT calibration and validation; [8], the 18 parameters were selected for discharge analysis, whereas the 11 variables were chosen to determine the sensitivity order for sediment model as shown in Fig. 14; [7]. There were three methods for calculating the appropriate variables used in the study: Absolute (A), Relative (R), and Replace Value (V) according to their minimum and maximum range. In this study, the objective function was expected to reach at least 0.7 of NSE.

3.4 Model Performance Evaluation

The coefficient of determination (R^2) and the Nash-Sutcliffe coefficient of model efficiency (NSE) to ensure the model performance with the observation data. The R-square ranges from 0 to1 and where the value close to 1 mean the model is well at expanding the resulting values with observation. The model consistency was implied by NSE value when NSE is nearly 1, referring highly efficient model. The equation for R^2 and NSE were shown in Eq.5 and Eq.6, respectively.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(X_i-\hat{X}_i)^2}{\sum_{i=1}^{n}(X_i-\bar{X})^2} \tag{5}$$

where R^2 is the coefficient of determination, X_i is the observed values, the $\hat{X}_i$ is the simulated values, and $\bar{X}$ is the mean of the observed data

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(X_i^{obs}-X_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(X_i^{obs}-X_i^{mean}\right)^2} \tag{6}$$

where NSE is the Nash-Sutcliffe model Efficiency coefficient, X_i^{obs} is the observed data, X_i^{sim} is the simulated data and X_i^{mean} is the average observed data

4. Results and Discussion

4.1 Discharge Evaluation

Table1 Model Performance for discharge evaluation

Station	Calibration Periods (2004 – 2006)		Validation Periods (2007 -2013)	
	R^2	NSE	R^2	NSE
061302 (2004-2013)	0.72	0.69	0.64	0.52
P.14 (2004-2008)	0.69	0.66	0.80	0.64
P.14A (2010-2013)	-	-	0.71	0.66

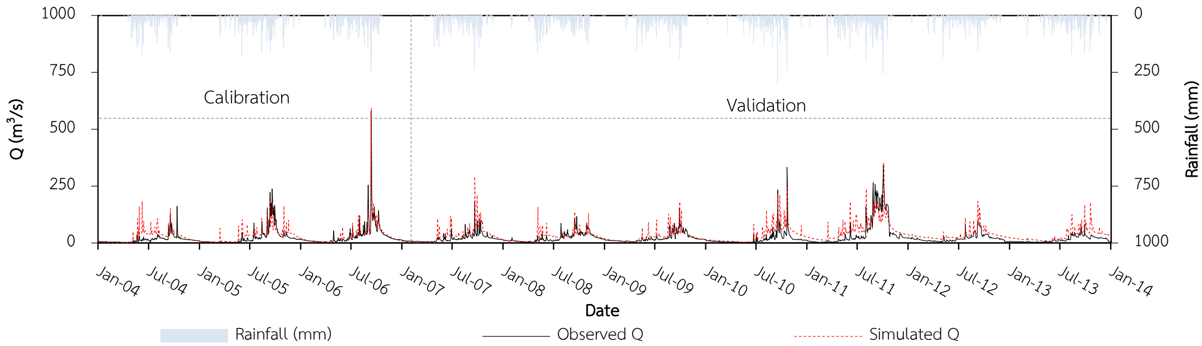

Fig.4 Hydrograph showing the comparison between observed and simulated outflow at 061302 in 2004 to 2013

The runoff was calibrated and validated at daily scale during 2004 to 2013. There are three available discharge gages locating in the study area, consist of station 061302, P.14, and P.14A. Station 061302 was used as a representative of the upstream and downstream stations of the Chaem River in 2004 to 2013, divided into 2 stations as P.14 and P.14A, located in Hang Dong, A. Hot, Chiang Mai. In particular, the station P.14 (Kaeng Ob Luang) was canceled in water year 2008 and a new monitoring downstream station was set up, Station P.14A (Ban Tha Kham). At station 061302 and P.14, the model performance for calibration period ranges from 0.72 to 0.66 for R^2 and 0.69 to 0.66 for NSE, given the satisfactory results as shown in Table 1. Considering R^2 and NSE values of the validation period at three main discharge stations also range from 0.80 to 0.64 and from 0.66 to 0.52, respectively. From discharge results of inlet station as 061302, covering drainage area of subbasin 1 to 5, in particular subbasin 5 where is the location of Mae Suk subdistrict, the 17% of subbasin is crop area during 2000. The main crop area is paddy field and is located near inlet station, therefore the water diversion was irrigated according to water demand for the cultivation; [9]. Therefore, the flowrate of the inlet channels trended to more sensitive than the downstream as P.14 and P.14A.

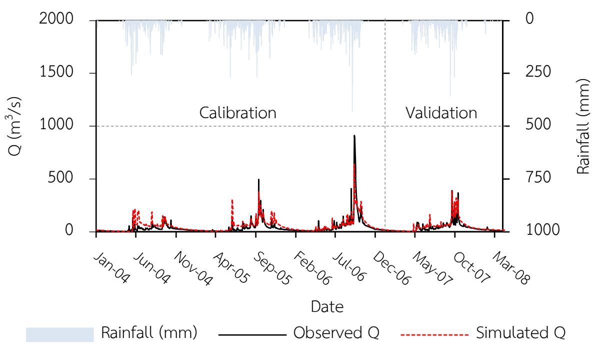

Fig. 5 Hydrograph showing the comparison between observed and simulated outflow at P.14 in 2004 to 2008

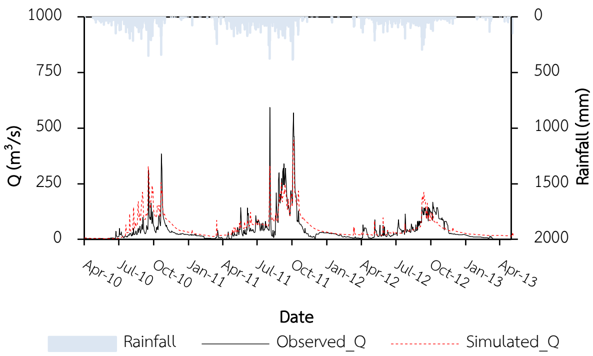

Fig. 6 Hydrograph showing the comparison between observed and simulated outflow at P.14A in 2010 to 2013

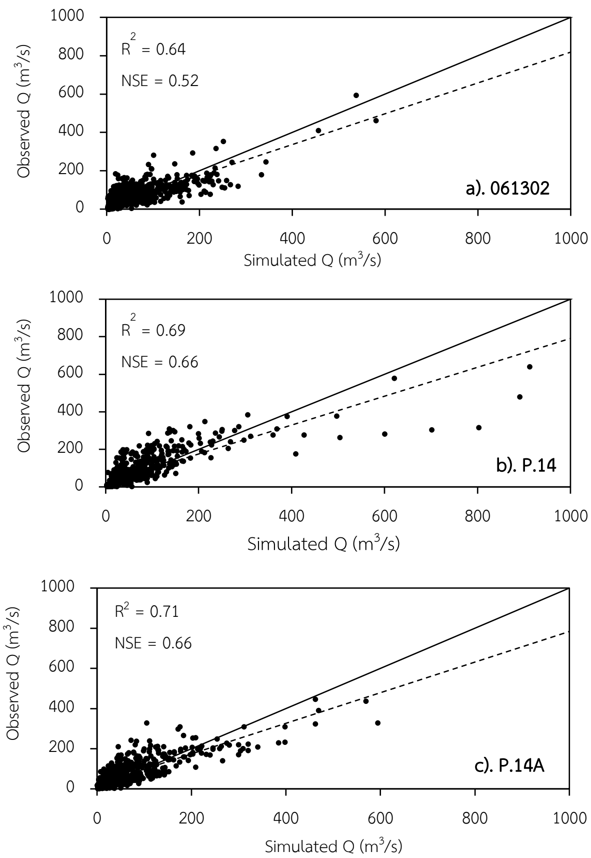

Fig 7. Relationship between simulated discharge and observed discharge at: a). 061302, b). P.14, and c). P.14A

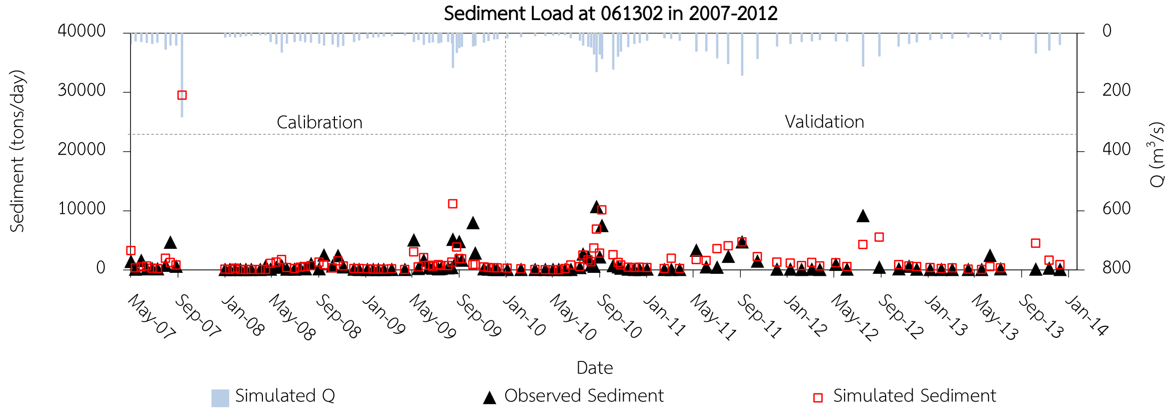

Fig.8 Predicted daily sediment graph at station 061302, during calibration and validation

4.2 Sediment Evaluation

4.2.1 Sediment flow

After the runoff model was considered as the satisfy level, the runoff model was used to assess daily suspended sediment transportation in 2004 to 2013. Additionally, the observed sediment data in this study is the sample test of sediment concentration that randomly collected in order to estimated daily sediment yield. The use of this type of data is expected to properly produce the reliable results to the local conditions. However, the sample data of sediment concentration collected along the Mae Chaem River at station 061302 was delivered only in 2007 to 2013, whereas, the limited sediment data was only lasted from 2004 to 2005. Unfortunately, sediment data has not collected at P.14A since downstream station was relocated. The R^2 and NSE at station P.14 of calibration period are 0.59 and 0.57, respectively. The R^2 values at station 061302 are 0.89 and 0.55, while the NSE values area equal to 0.79 and 0.46 for calibration and validation as shown in Table 2. The results of daily load were illustrated in Fig 9 to 10.

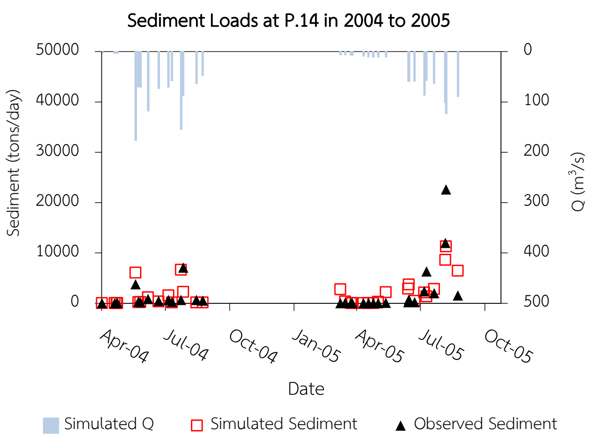

Fig.9 Estimated daily sediment graph at station P.14

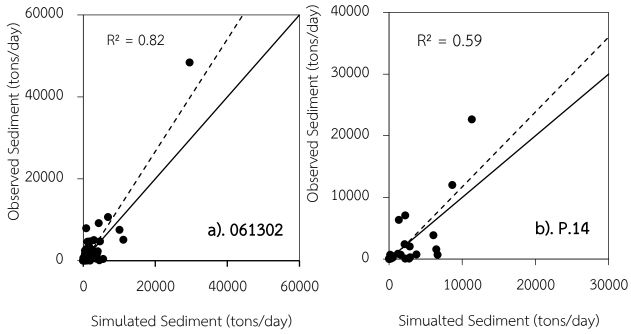

Fig 10. Relationship between simulated sediment and observed sediment for calibration and validation at: a). 061302, b). P.14

Table 2 Model Performance for sediment evaluation

Station	Calibration Period (2004-2009)		Validation Period (2011-2013)	
	R^2	NSE	R^2	NSE
061302 (2007-2013)	0.89	0.79	0.55	0.46
P.14 (2004-2005)	0.59	0.57	-	-

The modelling discrepancy might be caused by the soil series 62nd, which is called "slope complex or SC" and provided by LDD, corresponds to the topography of the mountainous area, making it more difficult to properly observe the soil characteristics. The predicted sediment that was transported from station 061302 was equal to 6,950,039 tons since 2004 to 2013. The average annual accumulative suspended sediment was approximately 1268.72 tons. At the downstream station, the sediment transport calculation has been assessed with the value of 8,632,348.13 tons at P.14 in 2004 to 2008, and 4,025,497.29 tons of transported sediment during 2010 to 2013 at station P.14A. The average annual transport of sludge is approximately 2,574.16 tons per year.

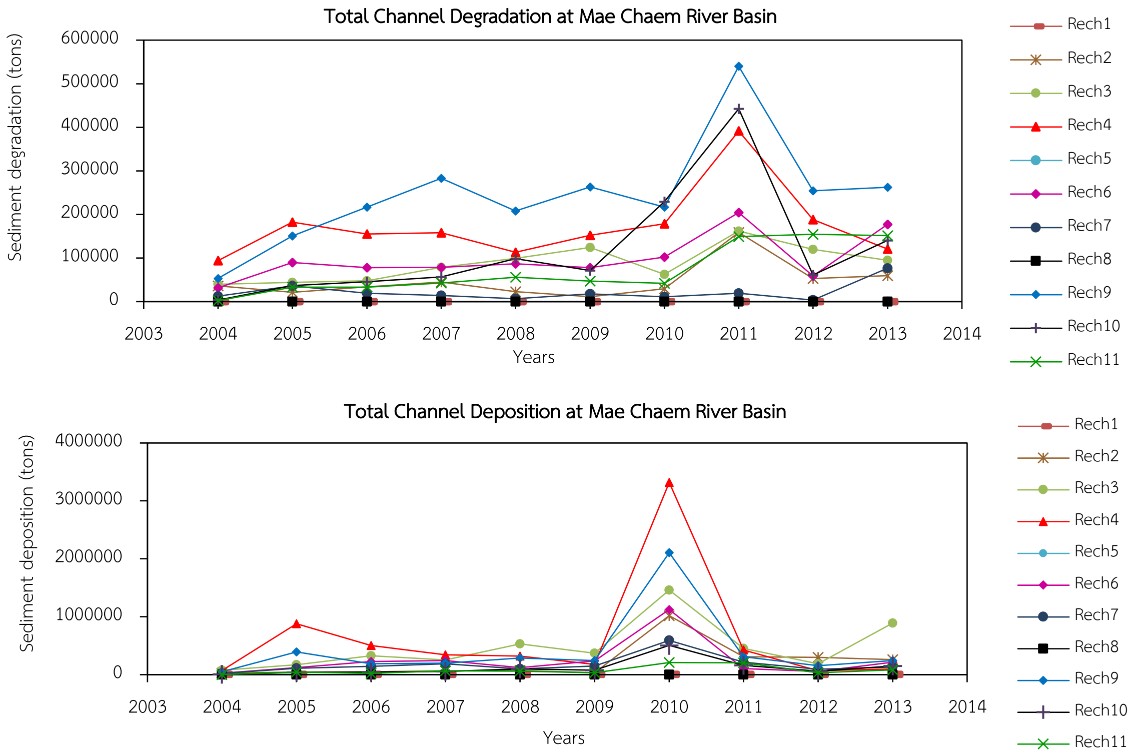

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Fig. 11 Sediment dynamic movement (Degradation and Deposition) along Mae Chaem River Basin since 2004 to 2010

4.2.2 The channel deposition and degradation

The movement of floating suspended sediments in the Mae Chaem River constantly changes the physical characteristics of the banks, effecting streamflow pattern and sediment deposition. The main stream river in study area was divided into 11 reach segments corresponded with subbasins. In SWAT model, the possible maximum concentration was estimated to assess the maximum of sediments that can be transported from the reach using the conceptual Bagnold equation and the condition of deposition and degradation. Furthermore, one of the historical great floods in Thailand emerging in 2011, the amount of rainfall and water volume in the northern region of Thailand was risen higher than usual condition. The highest of amount of sediment degradation has dramatically existed in 2011 which is approximately 539,946 tons, as illustrated in Fig 11. The total of sediment degradation from each reach segments is equal to 8,626,656.91 tons. The Annual average cumulative of sediment deposition was estimated at 784,240 tons/year. The most critical risk of banks erosion was notably appeared at T. Kong Khaek, T. Ban Thap and T. Bo Luang, crossing through subbasin 9 as illustrated in Fig.12. From the calculation result, the majority of deposition behavior was evidently distributed around subbasin 4, being 44% of the total of amount of channel deposition. The total deposited sediment was moved along the river, approximately 23,447,982.89 ton since 2004 to 2013. In particular, the behavior of channel deposition dominant distinguished in subbasin 3 to subbasin 4, covering T. Mae Na Chon, as exposed in Fig. 13.

4.3 Sensitivity Analysis

The 11 subbasin that spatially delineated by SWAT Model consists of 99 Hydrological Response Units (HRUs) regarding to the 5% of slope, soil and land use. In this study SWAT-Calibration and Uncertainty Programs (SWAT-CUP) was applied to estimate calibration and sensitivity analysis of SWAT Model that incorporate with the SUFI-2. The warm-up year of discharge model was executed within 2 years (2002 to 2003) for 3 years of calibration (2004 to 2006) and 7 years of validation (2007 to 2013), as well as, the sediment flow model used the same calculation range to evaluate susceptible variables of sediment yield. The optimal values of parameters were calculated within 2000 iterations. The relative correction in the model's input parameters also resulted in inconsequential changes of output. The sensitivity assessment has been assigned for streamflow based on p-value and t-test of parameters.

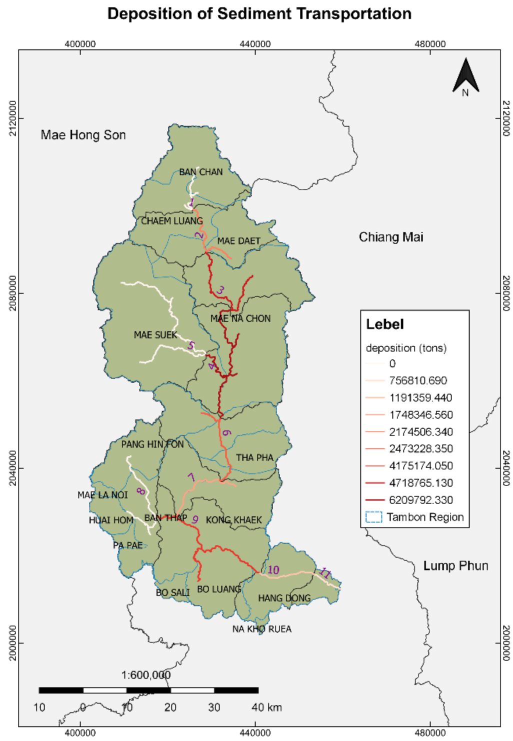

Fig. 12 Channel dynamical degradation in Mae Chaem River

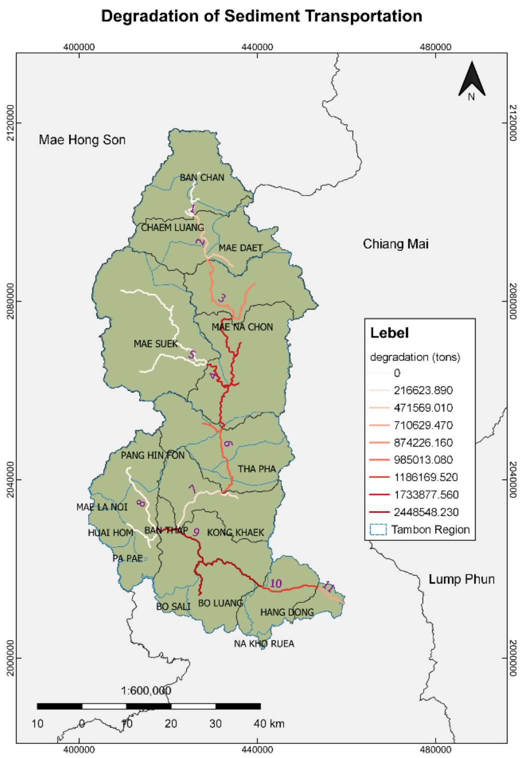

Fig.13 Channel dynamical deposition in Mae Chaem River

4.3.1 Sensitivity parameter of streamflow

In SWAT model, there are several variables involved effecting the discharge and sediment evaluations, sorted by cluster of soil, groundwater, river characteristics and weather variables. Furthermore, the sensitivity of SWAT parameters required for dynamic modification of parameters during the simulation. Therefore, the Sequential Uncertainty Fitting 2 (SUFI-2) in SWAT-CUP program was designed to assess the sensitivity and uncertainty of the indigenous SWAT models; [2]. Based on many literatures, the dominant parameters that were sensitive for flowrate assessment consist of SCS runoff curve number (CN2), Baseflow alpha factor (ALPHA_BF), Surface runoff lag time (SURLAG), Soil available capacity (SOL_AWC), Soil Evaporation Compensation Factor (ESCO) and Ground water delay (GW_DELAY); [10-11].

After, the selected eighteen parameters have been calculated and regulated using SUFI-2 methods. The notable parameter of streamflow simulation was ALPHA_BF, followed by CN2, ESCO, CH_N2 and GW_REVAP due to probability value, respectively. Whereas, the less relevant variables were subsisted to SOL_K, SLSUBBSN, SOL_AWC, USLE_K and GWQMN as shown in Fig14. From the results, it can be seen that the flow rate assessment is sensitive to numerous variables responding with groundwater, land use and land cover of each HRUs, soil characteristics and physical characteristics of the tributaries and main channel, respectively.

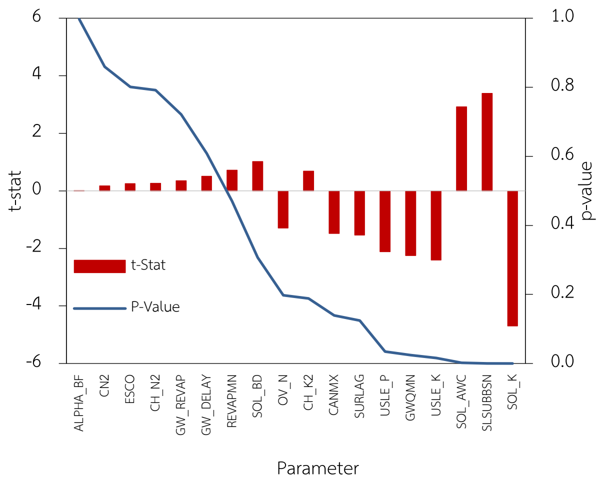

Fig.14 p-value and t-stat of the global sensitivity analysis from discharge model using SUFI-2 in SWAT-CUP

4.3.2 Sensitivity parameter of sediment flow

For the analysis of susceptible variables of the sludge yield model, it must be analyzed through runoff models with satisfactory assessment quality to obtain accurate results. The sediment models were concurrently established in several research found that the prevalent susceptible parameters, such as, channel cover factor (CH_COV), channel erodibility (CH_EROD), Linear parameter for calculating the maximum amount of sediment that can be reetrained during channel sediment (SPOCN), Exponent parameter for calculating sediment reetrained in channel sediment routing (SPEXP), and USLE equation support practice factor (USLE_P); [12] All related 11 variables were analyzed in the same manner as flow rate analysis. From the calculation, the dominant sensitive variable was USLE_P toward to USLE_K, ALPHA_BNK, SPCON, SPEXP and CH_COV1 in accordance to p-value. In addition, the variables that were less than 20 percent susceptible to the model were CH_COV2, CH_ERODMO, ADJ_PKR, CH_D50 and EROS_EXPO, respectively as shown in Fig.15. Moreover, the results showed that the evaluation of suspended sediment flow in the Mae Chaem River Basin was more likely to be affected by land practice and soil erodibility than the physical channel characteristics. Therefore, change in land use was probably the main cause of incompatibility between simulation and observed data over the study period.

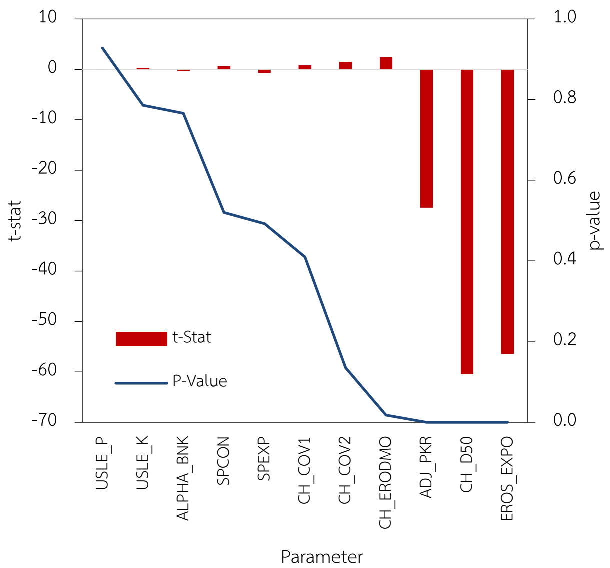

Fig.15 p-value and t-stat of the global sensitivity analysis from sediment model using SFUI-2 in SWAT-CUP

5. Conclusion

Effective model calibration is essential for effective results in the case of hydrological assessments. In this study, the SWAT model was calibrated to analyze the flow rate of the Mae Chaem River Basin. The watershed HRUs were spatially determined based on soil data, slope and land use characteristics. The efficient runoff models resulted in a consistent reliable assessment of sediment loads in the study area. The results showed the reliable of daily flow estimation with the satisfied statistical modelling (R^2 and NSE) during the calibration and validation period. The daily sediment load simulation also replied on the acceptable results at station 061302 and provided the satisfactory at station P.14 for the whole period.

The sediment transportation was compensated using the MUSLE equation of channel routing with the higher rate of channel deposition rather than channel degradation. The soil erosion and sediment transport in Mae Chaem River Basin corresponds with the amount of runoff volume, particularly during 2011 that channel segment 9 apparently produced the highest rate of degraded sediment load. In addition, sediment dynamic evaluation predictably explored where the majority of sediment deposition occurred at T. Mae Nam Chon, covering the river bank in subbasin 3 and 4. Although, the cluster of critical channel degradation was found at downstream, occupying the area of T. Kong Khaek, A. Mae Chaem and T. Bo Luang, A. Hot, Chiang Mai province during 2004 to 2013.

However, the uncertainty of prediction that failed to combine the observed data shown the underestimation and overestimation results in both modelling. The SWAT-CUP program was utilized to study variables sensitive to the assessment of flow rates and sediment yields in this study. The four outstanding variables most sensitive to flow rate assessments are ALPHA_BF (Baseflow recession constant), CN2 (Moisture condition II curve number), ESCO (Soil evaporation compensation coefficient) and CH_N2 (Manning's n value for the main channels). While the first four variables that are likely to induce significant changes in the sediment yield model are USLE_P (USLE support practice (P) factor), USLE_K (USLE soil erodibility (K) factor), ALPHA_BNK (Baseflow alpha factor for bank storage), and SPCON (Linear parameter calculating the maximum of sediment that can be reentrained during channel sediment routing.

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