Assessment of sediment yield in Thailand using revised universal soil loss equation and geographic information system techniques

著者	Prem Rangsiwanichpong, So Kazama, Luminda Gunawardhana
journal or publication title	River Research and Applications
volume	34
number	9
page range	1113-1122
year	2018-11-08
URL	http://hdl.handle.net/10097/00126477

doi: 10.1002/rra.3351

Assessment of sediment yield in Thailand using RUSLE and GIS techniques

Prem Rangsiwanichpong[1*], So Kazama[2], Luminda Gunawardhana[3]

[1]Graduate School of Environmental Studies, Tohoku University, Sendai, 980-8579, Japan
[2]Graduate School of Engineering, Tohoku University, Sendai, 980-8579, Japan
[3]Department of Civil and Architectural Engineering, College of Engineering, Sultan Qaboos University, Oman.

Correspondence to: Prem Rangsiwanichpong (prem.rangsiwanichpong.q8@dc.tohoku.ac.jp)

Abstract. Soil is one of the most important natural resources on Earth. Information on soil loss is important to support agricultural productivity and natural resource management. Therefore, this research aimed to estimate and map mean annual soil erosion and sediment deposition using a geographic information system (GIS). The soil loss in each grid cell was analyzed by the revised universal soil loss equation (RUSLE) model. The parameters of the RUSLE including rainfall, soil type, and land use were calculated in each grid cell from a digital elevation model with of 1 square kilometer resolution. Furthermore, sediment deposition was derived from the RUSLE model and used in GIS software to generate soil loss capacity maps. The results show that soil erosion occurred over all parts of Thailand, especially in the northern and southern parts due to the topography, geology and land cover. The sediment was deposited in grid cells where the elevation was low, primarily near rivers. The results of this research support local land development policies that are implemented to control sediment yields during development.

Keywords: Deposition, Erosion, GIS, Spatial distribution, Thailand

1 Introduction

Every year, millions of tons of sediment are produced around the world. One major source of sediment is fluvial erosion (Elirehema, 2001). Fluvial erosion also delivers millions of tons of sediment to dams, reservoirs, lakes, and oceans (Chakrapani, 2005; Walling, 2006). Sediment deposition and erosion can impact dam facilities, water quality, and agriculture activities. Dams and reservoirs around the world have mostly been used to produce energy and supply water for irrigation. Several studies have indicated that sediments can significantly reduce the storage and power generation capacities of dams and reservoirs (Wang et al., 2007; Vaezi et al., 2017). Sabir et al. (2013) analyzed the impacts of sediment yields on the Warsak Reservoir and energy production in Pakistan. They found that the power production in the Warsak Reservoir has decreased by approximately 70% due to sediment deposition.

Soil erosion represents the amount of soil moved from one particular area to another in the form of sediment. This phenomenon depends on the relationships between rain, runoff and erodibility of each area. Previous research has reported the impacts of climate variability on soil erosion (Asselman et al., 2003; Syvitski et al., 2003; Mukundan et al., 2013). As the climate changes, the intensity and frequency of extreme rainfall events will likely increase in the future, resulting in more soil erosion and higher sediment yields (Kostaschuk et al., 2002; Bouraoui et al., 2004). For example, Rodríguez-Blanco et al. (2016) projected that climate change will likely have a noticeable impact on sediment yields in NW Spain. They predicted that suspended sediment concentrations in 2031-2060 and 2069-2098 may decrease by 11% and 8%, respectively, compared with those in 1981-2010 due to the decrease in streamflow. In contrast, they estimated that sediment transport may increase by 11-17% in the winter seasons of 2031-2098 due to increased erosion in cultivated areas.

Furthermore, vegetation cover has a significant effect on runoff and sediment yields. Numerous studies have investigated the effects of land use change on soil erosion (Mohamad and Adam, 2010; Li et al., 2014; Wang et al., 2016). For example, Son et al. (2015) attributed 88% and 46% of the increases in annual runoff and sediment yield, respectively, to the changes in land use types in the Da River basin in Vietnam between 1995 and 2005. In a recent study, Zare et al. (2017) simulated the impacts of future land use change on soil erosion in Iran and found that the mean soil erosion potential could increase by 45% in 2030 compared with average conditions from 1980-2011.

The deterioration of water quality due to increased sediment yields may negatively affect the economy and industrial, urban, agricultural and aquaculture activities in many countries around the world. Highly erosive soil together with extreme rainfall may produce runoff with large amounts of sediment and high concentrations of pollutants such as cadmium, phosphorus and heavy metals (Rodríguez et al., 2013; Tang et al., 2014; Somprasong and Chaiwiwatworakul, 2015). These impacts indicate the importance of quantifying sediment yields in watersheds for the sake of managing and making decisions about the water resources in the region.

For the past few decades, numerical, empirical, and field experiment methods have been employed to investigate soil erosion and deposition (Curtis et al., 2006; Gelagay and Minale, 2016; Noori et al., 2016). The universal soil loss equation (USLE) model (Wischmeier and Smith, 1978) is one of the most widely used models for analyzing soil erosion and sediment yields. This method, in combination with geographic information systems (GIS) and remote sensing data, has been used to estimate long-term soil erosion even in sloped areas based on the knowledge of soil and physical parameters (Pandey et al., 2007; Jain and Das, 2010). However, various studies have identified limitations of using the USLE method, such as the lack of input parameters to run the model in ungauged basins (Loch and Rosewell, 1992), long-term data requirements and large resources required to develop the input data for a new area (Nearing et al., 1994) and difficulty estimating erosion at large spatial scales (Zhang et al., 1995). Consequently, modified techniques such as the USLE-M, revised USLE (RUSLE) and modified USLE (MUSLE) have been developed. Moreover, the erosion potential method (EPM), an empirical model developed by the Food and Agriculture Organization (FAO), has been employed by the Pacific Southwest Inter-Agency Committee (PSIAC).

Previous studies have investigated sediment sources and soil erosion using lump models as well as distributed models. However, a greater understanding of soil deposition, as well as soil erosion, is of prime importance for planning counter measures. Models that were employed in previous studies were capable of simulating only sediment erosion and were unable to predict the spatial distribution of soil deposition. The objective of this study is to develop a technique that is capable of estimating the spatial distribution of both soil erosion and deposition in a watershed by modifying the original RUSLE method.

2 Study area and data

Thailand is located in the center of the Southeast Asian peninsula. The topography of Thailand can be separated into 5 major physical regions consisting of the central valley, the northern plateau area, the northwest, the northeast, the southeastern coast, and the peninsula. Approximately 20% of Thailand is covered by mountain and hills, especially in the northern and southern regions. Thailand has a tropical monsoon climate characterized by a dry season from November to April and a wet season from May to October. The annual rainfall in the country is 1150 mm: approximately 988 mm (82%) falls during the wet season, and around139 mm (18%) falls during the dry season. The agricultural areas represent more than 40% of the country (World Bank, 2014). The agriculture has developed from subsistence farming to cash crops since the 1960s. This development has resulted in the alteration of forest to agriculture areas. The speed of deforestation and the effects of soil loss on agriculture areas has resulted in significant resource degradation. In this research, we used 45 hydrological stations operated by the Royal Irrigation Department (RID) to observe sediment discharge (Fig. 1). These stations were selected to cover all of Thailand with monthly sediment data from 1998 to 2014 (16 years). Furthermore, we obtained the daily rainfall data from 150 stations during the same period from the Thai Meteorological Department (TMD).

3 Methodology

This research aims to develop a model that uses remote sensing and GIS data to analyze the spatial distribution of soil erosion and sediment deposition in Thailand. The ArcGIS software package was used to input the data at grid scales and to calculate soil erosion according to Equation (1).
In this research, the soil erosion in each grid cell was estimated using the RUSLE (Renard et al., 1997). The RUSLE has been widely used around the world in forests, mountains and agricultural areas to predict average annual soil loss. It is an empirical model that can be expressed as follows.

$$A = R \times K \times LS \times C \times P \qquad (1)$$

where A = annual soil loss per unit area ($TON \cdot ha^{-1} \cdot year^{-1}$); R = rainfall erosivity factor ($MJ \cdot mm \cdot ha^{-1} \cdot hr^{-1} \cdot year^{-1}$); K = soil erodibility factor ($TON \cdot hr \cdot MJ^{-1} \cdot mm^{-1}$); LS = slope and length factor (dimensionless); C = cover-management factor (dimensionless); and P = conservation practice factor (dimensionless).

The Land Development Department of Thailand (LDD) recommended the following equation for calculating the rainfall erosivity factor (R) as follows:

$$R = 0.4669X - 12.141559 \quad (2)$$

where R = rainfall erosivity factor ($MJ \cdot mm \cdot ha^{-1} \cdot hr^{-1} \cdot year^{-1}$) and X = annual rainfall (mm).

The slope of a basin has a major effect on soil erosion. A higher slope results in a greater velocity of overland flow and increased shear stress on soil particles. We analyzed the percentage of slope steepness using a digital elevation model (DEM) obtained from U.S. Geological Survey with 1 km^2 resolution. The slope factor (S) in the RUSLE was calculated under two categories; slope gradients less than 9% (Equation 3) and greater than 9% (Equation 4). The LS factor for each grid cell was calculated as in Equations 3, 4, 5, and 6.

$$S_{\text{factor}} = 10.8 \sin\theta + 0.03 \quad (3)$$

$$S_{\text{factor}} = 16.8 \sin\theta + 0.5 \quad (4)$$

$$L_{\text{factor}} = \left(\frac{\lambda}{22.12}\right) \times \left(\frac{\frac{\left(\frac{\sin\theta}{0.0896}\right)}{(3\sin\theta \times 0.8 + 0.56)}}{1 + \frac{\left(\frac{\sin\theta}{0.0896}\right)}{(3\sin\theta \times 0.8 + 0.56)}}\right) \quad (5)$$

$$LS = L_{\text{factor}} \times S_{\text{factor}} \quad (6)$$

where λ = length of slope; L_{factor} = slope length factor; and S_{factor} = steepness factor.

The P factor expresses the effect of conservation practices that reduce the amount and rate of water runoff and subsequent soil erosion. P factor values were divided into 6 slope classes for the agricultural areas, as shown in Table 1 (Wischmeier and Smith, 1978). The K factor integrates the effects of overland flow and resistance of soil to particle detachment and subsequent transport. In this research, K factors were collected from the Land Development Department of Thailand.

The C factor expresses the effects of cropping and management practices on the rate of soil erosion. As vegetation cover increases, soil loss decreases. Several studies have estimated vegetation cover from the normalized difference vegetation index (NDVI; Zhang et al., 2006; Buyantuyev et al., 2007). The NDVI is an effective remote sensing indicator of green vegetation distribution that is derived by determining the difference between the spectral reflectance values between the near infrared (NIR) and red (RED) bands of the electromagnetic spectrum (Rouse et al., 1974). Theoretically, the NDVI value ranges between -1 to 1 and can be calculated as follows:

$$\mathrm{NDVI} = \frac{\mathrm{NIR}-\mathrm{RED}}{\mathrm{NIR}+\mathrm{RED}} \tag{7}$$

The C factor is then derived according to Equation 8 (Farhan Y. et al., 2013).

$$C = (-0.7388 \times \mathrm{NDVI} + 0.4948) \tag{8}$$

A new technique was developed to estimate the capacity of sediment yield or deposition in each subcatchment by modifying the original RUSLE method. It was assumed that the amount of sediment flow from one grid cell to another downstream grid cell depends on the sediment yield of the original grid cell (S_y) compared to the average sediment yield capacity of the whole catchment (S_c). Altogether, 256 catchments were considered, and average spatial parameters were calculated for each catchment. If S_y is greater than S_c, transportation occurs. Conversely, when S_y is less than S_c, sediment is deposited. S_c was calculated using the original RUSLE with the area-averaged parameters (Equation 10). Similarly, the sediment yield of a particular grid cell was calculated using the individual parameters assigned for that grid cell (Equation 9).

$$S_y = f(I_1, I_2, \ldots, I_5) \tag{9}$$

$$S_C = f\left(\frac{\sum_{i=1}^{n} I_1}{A}, \frac{\sum_{i=1}^{n} I_2}{A}, \ldots, \frac{\sum_{i=1}^{n} I_5}{A}\right) \tag{10}$$

$$D_i \; if \; S_y < S_C \tag{11}$$

$$T_i \; if \; S_y > S_C \tag{12}$$

where S_y = sediment yield, S_C = sediment capacity, I_i = parameters in the RUSLE model, A = area of the subcatchment, n = number of data in each sub-basin, D_i = deposition in cell i , and T_i = transportation in cell i.

The spatial distribution of the sediment yield and deposition was estimated by the above equation. Such understanding will be of prime importance for future developments in the watershed.

A number of studies have assessed sediment yield using different hydrological models. One widely used technique for analyzing sediment transport is the rating curve method (Walling, 1983). Wongsa and Shimizu (2001) combined a hydrological model with the rating curve method to estimate sediment yield in Japan and compared their results with real events. Furthermore, Kazama et al. (2005) calibrated the parameters of the rating curve method in the Mae Kong River basin in northeast Thailand. In their study, the P factor was calculated from the sediment observations and slope gradients. Similarly, the K parameter was estimated as an exponential function of slope gradient, roughness, and the averaged diameter of sediment particles as follows. (Equation 13, 14, 15)

$$Q_s = KQ^P \tag{13}$$

$$P = 19I^{-0.497}d + 1 \tag{14}$$

$$K = (\frac{n}{0.02})^{P+1} 0.0003I^{-0.146} \exp((1.01\ln(I) + 5.08) \times 10^4 d) \tag{15}$$

where Q_s = sediment discharge (m^3/s^{-1}); Q = water discharge (m^3/s^{-1}); P and K = model parameters; I = slope gradient; d = diameter of sediment (m); and n = roughness. In the current study, the method proposed by Kazama et al. (2005) was used to compare the results obtained from the method previously applied.

4 Results and discussion

4.1 Generation potential according to the soil erosion map

In this research, the RUSLE method was used with remote sensing and GIS to investigate the spatial distribution of the average annual soil erosion in Thailand. The five parameters presented in Equation 1 were determined and assigned to each grid cell. The erosivity factors (R) determined by annual precipitation at metrological stations were interpolated by the inverse distance weighted (IDW) method using the ArcGIS spatial analyst tool for 1998 to 2014. The result indicates that the erosivity factor for Thailand ranges from 369.1 to 1788.4 with greater values occurring in the southern part of the country (Fig. 2).

In addition, the slope factor (LS) is an important parameter of soil erosion to consider. The results of the LS factor show that high values occurred in the mountainous areas of Thailand (Fig. 3A). Overland flow with greater velocities is attributed to the steeper slopes in mountainous areas, and these conditions augment the soil erosion in downstream areas of the watershed.

The erodibility factor (K) depends on the soil type. In this analysis, data obtained from the Land Development Department of Thailand was used. Three soil types, sand, silt, and clay were distinguished and identified, and the corresponding standard K values recommended by the Land Development Department (LDD) of 0.05, 0.19, and 0.3 for clay, silt, and sand, respectively, were assigned to each grid cell (Fig. 3B). In general, silt and sand particles are easily detachable and highly erodible and as a result their K factors are higher than that of clay.

The C factor represents the impact of cropping and cultivation practices on soil erosion in an agricultural area. According to Farhan et al. (2013), the C factor is calculated from the NDVI value of the study area. Smaller C values indicate denser vegetation cover and therefore less runoff and soil erosion potential. The results show that higher C factor values (0.2-0.6) occurred in the downstream areas of the basin (Fig. 4A). Essentially, downstream areas in Thailand are covered by agricultural landuse such as cassava and paddy fields. The results indicate that crops such as cassava and rice provide limited soil erosion protection compared to natural vegetation cover, such as the forest area in northern Thailand (Lorsirirat and Maita, 2006).

The P factor represents the effects of soil conservation practices to reduce soil erosion. The value of P ranges between 0 and 1. A P value close to 1 indicates poor conservation practices and a value closer to 0 indicates good conservation practices. The results show that most of the upstream areas have P values approximately equal to 1 (Fig. 4B), which indicates that erosion management practices have not been implemented in these areas. In contrast, deforestation in upstream areas for agricultural activities has had a significant effect on soil erosion.

After all parameters were assigned to each grid cell, soil erosion was calculated according to Equation 1. The results indicate that the average annual soil erosion in Thailand is approximately 650 m3·km-2·year-1. Figure 5 illustrates that different magnitudes of soil erosion occurring in every part of Thailand, but also shows significantly higher magnitudes occur in the northern and southern parts of the country. This result can be attributed to the effects of the topography, geology and land cover, which have the potential to enhance erodibility.

4.2 Estimation of sediment capacities and identification of deposition areas

The analysis method to identify the sediment deposition areas of Thailand was developed by modifying the original RUSLE method. The sediment yield capacity of the whole catchment was estimated by the spatially averaged parameters assigned in the RUSLE method. Figure 6A shows that the northwest of the country has a higher sediment yield than the other areas. The average catchment sediment yield capacity was then compared with the sediment yield estimated in each grid cell. If the calculated sediment yield potential in a grid cell was smaller than the average value, that grid cell was considered to be a deposition cell. The magnitude of the difference of the negative values shown in Figure 6B indicates the capacity of sediment deposition in each grid cell. In contrast, when the calculated sediment yield potential in a grid cell was higher than the averaged catchment value, sediment erosion occurs. The grid cells with positive values in Figure 6B indicates the areas estimated to be susceptible to sediment erosion.

The spatially averages annual sediment deposition potential in Thailand is 257 m^3km^{-2} $year^{-1}$.Higher sediment deposition may occur in the northern part of Thailand, especially upstream of the Chao Phraya River basin and in the Pa Sak River basin, with approximate average values of 600 $m^3\cdot km^{-2}\cdot year^{-1}$ (Figure 6B). Sediment deposition upstream of the Chao Phraya River basin mostly occurred in areas close to the river where the elevation is low (Figure 7). Furthermore, it is evident that sediment is moved from the mountainsides to valley bottom areas by runoff and it is deposited in floodplain and impounded areas. For verification, the spatial distribution of the sediment deposition and erosion as estimated in Figure 7 was compared with the topography map of Thailand. The net sedimentation map generally matched the variations in topography in the study area. A comparison between the net sedimentation map and the topography map for the upper Mae Klong River basin (Figure 8). The results indicated that upstream of Mae Klong River basin does not have many tributaries, yet sediment is deposited in a large proportion of the basin. Soil that is eroded from mountainous areas is carried by overland flow and settles in downstream lowland areas. These results, therefore, suggest that the proposed method can simulate sediment erosion and deposition successfully in the presence of different transport mechanisms such as river flow and overland flow.

4.3 Verification

The results from the net sediment map were verified by observed sediment data at 45 stations. The match between the observed data and the sediment data simulated by the proposed technique shows good agreement with a correlation higher than 0.9 (Fig. 9A). A comparison of the sediment yield with data observed from sediment stations in downstream areas is not sufficient to validate the spatially distributed sediment model because of the highly complex behaviors of sediment in downstream areas (Takkena et al., 1999). Therefore, a rating curve was also applied with the same parameters calibrated by Kazama et al. (2005) in northeast Thailand. A comparison was made between the results obtained with the proposed method and the rating curve method. The results show that both methods can predict the potential sediment yields (Fig. 9B). The strong correlation between the sediment yields estimated by the new technique and the rating curve method indicates that this method can be used to estimate sediment yields in Thailand (Fig. 9C). These results also indicates that this method can be applied to any poor gaged area with low cost

5 Conclusions

The goals of this study were to develop a method that can simulate both soil erosion and deposition using RUSLE models in Thailand. Altogether, 256 catchments covering all of Thailand and sediment data from 45 stations were used. The results indicate that soil erosion can occur in every part of Thailand, but higher potential rates occur in northern and southern regions due to the combined effects of topography, geology and land cover. Sediment deposition probably occurs in lower elevation areas, mostly along river margins, by both river flow and overland flow. The maps produced indicate the spatial distribution of sediment erosion and deposition depict that high sediment deposition may occur in the northern part of Thailand, especially upstream of the Chao Phraya River basin and in the Pa Sak River basin. These results were compared with the sediment yield estimated by the rating curve method. The results show that the sediment yields simulated by the two methods are highly correlated. Both methods also show reasonable matches with the observed sediment yield at 45 catchment outlets. The results, therefore, suggest that the proposed method can be used to estimate sediment yield in Thailand.

This research successfully produced maps of both soil erosion and deposition covering large areas. The proposed method can be applied not only in Thailand but also other countries. The results can be used to manage water resources and plan countermeasures in the face of climate change and subsequent soil erosion. However, the applicability of this method must be tested in other study areas with various climatic and geographical settings.

Acknowledgments

This study was supported by Advancing Co-design of Integrated Strategies with Adaptation to Climate Change (ADAP-T) of JST/JICA, SATREPS. This study was carried out by the Program for Leading Graduate Schools, Tohoku University and the "Inter-Graduate School Doctoral Degree Program on

Global Safety," of the Ministry of Education, Culture, Sports, Science and Technology. The authors wish to thank the Thai RID for providing the sediment data.

References

Asselman, N. E. M., Middelkoop, H., & Dijk, P.M. (2003). The impact of climate change on soil erosion, transport and deposition of suspended sediment in the river Rhine. Hydrol. Processes, 17(16), 3225 – 3244. DOI:10.1002/hyp.1384

Bouraoui, F., Grizzetti, B., Granlund, K., Rekolainen, S. & Bidoglio, G. (2004). Impact of climate change on the water cycle and nutrient losses in a Finnish catchment. Climatic Change, 66(1-2), 109–126. https://doi.org/10.1023/B:CLIM.0000043147.09365.e3

Buyantuyev A., Wu J., & Gries, C. (2007). Estimating vegetation cover in an urban environment based on Landsat ETM + imagery: A case study in Phoenix, USA. International Journal of Remote Sensing, 28(2), 269–291. doi:10.1080/01431160600658149

Chakrapani, G. J. (2005). Factors controlling variations in river sediment loads. Current Science, 88(4), 569–575.

Crutis, J. A., Flint, L. E., Alpers, C. N., & Wright, S. A. (2006). Evaluating sediment sources, erosion, and transport processes in the upper Yuba River Watershed, California. In *Proceeding of 8th Federal Interagency Sedimentation Conference (FISC)*, pp.450-456.

Elirehema, Y. S. (2001). Soil Water Erosion Modeling in Selected Watersheds in Southern Spain, IFA, ITC, Enschede, Netherland.

Farhan, Y., Zregat, D., & Farhan, I. (2013). Spatial estimation of soil erosion risk using RUSLE approach, RS, and GIS techniques: A case study of Kufranja watershed, Northern Jordan. Journal of Water Resource and Protection, 5, 1247-1261. doi:10.4236/jwarp.2013.512134

Gelagay, H. S., & Minale, A. S. (2016). Soil loss estimation using GIS and Remote sensing techniques: A case of Koga watershed, Northwestern Ethiopia. International Soil and Water Conservation Research, 4(2), 126-136. http://dx.doi.org/10.1016/j.iswcr.2016.01.002

Jain, M. K., & Das, D. (2010). Estimation of sediment yield and areas of soil erosion and deposition for watershed prioritization using GIS and remote sensing. Water Resources Management, 24(10), 1091-2112. DOI:10.1007/s11269-009-9540-0

Kazama, S., Suzuki, K., & Suwamoto, M. (2005). Estimation of rating-curve parameters for sedimentation using a physical model. Hydrological Processes, 19(19), 3863-3871. DOI: 10.1002/hyp.5986

Kostaschuk, R., Terry, J., & Raj, R. (2002). Suspended sediment transport during tropicalcyclone floods in Fiji. Hydrological Processes, 17(6), 1149–1164. DOI:10.1002/hyp.1186

Li, X. H., Yang, J., Zhao, C. Y. & Wang, B. (2014). Runoff and sediment from orchard terraces in southeastern China. Land Degradation and Development, 25(2), 184-192. DOI:10.1002/ldr.1160

Loch, R., & Rosewell, C. (1992). Laboratory methods for measurement of soil erodibilities (K factors) for the universal soil loss equation. Australian Journal of Soil Research, 30(2), 233-248.

Lorsirirat, K., & Maita, H. (2006). Soil Erosion Problems in Northeast Thailand: A Case Study from the View of

Agricultural Development in a Rural Community Near Khon Kaen. Universal Academy Press, Inc. Tokyo, Japan, 675-686.

Mohammad, A. G., & Adam, M. A. (2010). The impact of vegetative cover type on runoff and soil erosion under different land uses. Catena, 81(2), 97-103. doi:10.1016/j.catena.2010.01.008

Mukundan, R., Pradhanang, S. M., Schneiderman, E. M., Pierson, D. C., Anandhi, A., Zion, M. S., ... Steenhuis, T. S. (2013). Suspended sediment source areas and future climate impact on soil erosion and sediment yield in a New York City water supply watershed, USA. Geomorphology, 183, 110-119. http://dx.doi.org/10.1016/j.geomorph.2012.06.021

Nearing, M. A., Lane, L. J., & Lopes, V. L. (1994). Modeling soil erosion. In: Soil erosion research methods, in R. Lal (Eds), Soil and Water Conservation Society (pp. 127-156). St Lucie Press.

Noori, H., Siadatmousavi, S. M., & Mojaradi, B.(2016). Assessment of sediment yield using RS and GIS at two sub-basins of Dez Watershed, Iran. International Soil and Water Conservation Research, 4(3), 199-206. http://dx.doi.org/10.1016/j.iswcr.2016.06.001

Pandey, A., Chowdary, V. M., & Mal, B. C. (2007). Identification of critical erosion prone areas in the small agricultural watershed using USLE, GIS and remote sensing. Water Resources Management, 21(4), 729-746. DOI:10.1007/s11269-006-9061-z

Renard, K., Foster, G., Weesies, G., McCool, D., & Yoder, D. (1997). Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). USDA Agriculture Handbook, 703.

Rodríguez-Blanco M.L., Arias, R., Taboada, M. M., Nunes, J. P., Keizer, J. J., & Taboada, M. T. (2016). Potential Impact of Climate Change on Suspended Sediment Yield in NW Spain: A Case Study on the Corbeira Catchment. Water, 8(10), 444, doi:10.3390/w8100444

Rodríguez, M. L., Taboada, M. M., & Taboada, M. T. (2013). Phosphorus transport into a stream draining from a mixed land use catchment in Galicia (NW Spain): Significance of runoff events. Journal of Hydrology, 481, 12-21, DOI:10.1016/j.jhydrol.2012.11.046

Rouse, J. W., Haas, R. W., Schell, J. A., Deering, D. W., & Harlan, J. C. (1974). Monitoring the vernal advancement and retrogradation (greenware effect) of natural vegetation. Greenbelt, MD, USA, NASA/GSFCT, Type 3, Final Report.

Sabir, M. A., Shafiq, S., Umar, M., Waseem, A., Farooq, M., & Khan, A. R. (2013). The impact of suspended sediment load on reservoir siltation and energy production: a case study of the Indus river and its tributaries. Pol. J. Environ Stud, 22(1), 219−225.

Somprasong, K., & Chaiwiwatworakul, P. (2015). Estimation of potential cadmium contamination using an integrated RUSLE, GIS and remote sensing technique in a remote watershed area: a case study of the Mae Tao Basin, Thailand. Environmental Earth Sciences, 73(8), 4805–4818. DOI:10.1007/s12665-014-3766-8

Son, T. N., Binh, N. D., & Shrestha, R. P. (2015). Effect of land use change on runoff and sediment yield in Da River Basin of Hoa Binh province, Northwest Vietnam. Journal of Mountain Science, 12(4), 1051-1064. DOI:10.1007/s11629-013-2925-9

Syvitski, J. P. M., Peckham, S. D., Hilberman, R., & Mulder, T. (2003). Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. Sedimentary Geology, 162(1-2), 5-24. http://dx.doi.org/10.1016/S0037-0738(03)00232-X

Takkena, I., Beuselincka, L., Nachtergaelea, J., Goversb, G., Poesenb, J., & Degraera, G. (1999). Spatial evaluation of a physically-based distributed erosion model (LISEM). Catena, 37(3-4), 431–447. https://doi.org/10.1016/S0341-8162(99)00031-4

Tang, W., Shan, B., Zhang, H., Zhang, W., Zhao, Y., Ding, Y., ... Zhu, X. (2014). Heavy Metal Contamination in the Surface Sediments of Representative Limnetic Ecosystems in Eastern China. Scientific Reports, 4, 7152, http://doi.org/10.1038/srep07152

Vaezi, A. R., Abbasi, M., Keesstra, S., & Cerda, A. (2017). Assessment of soil particle erodibility and sediment trapping using check dams in small semi-arid catchments. Catena, 157, 227-240. https://doi.org/10.1016/j.catena.2017.05.021

Walling, D. E. (2006). Human impact on land-ocean sediment transfer by the world's rivers. Geomorphology, 79(3-4), 192–216. http://dx.doi.org/10.1016/j.geomorph.2006.06.019

Walling, D. E. (1983). The sediment delivery problem. Journal of Hydrology, 65(1-3), 209-237. https://doi.org/10.1016/0022-1694(83)90217-2

Wang, X., Zhao, X., Zhang, Z., Yi, L., Zuo, L., Wen, Q., ... Liu, B. (2016). Assessment of soil erosion change and its relationships with land use/cover change in China from the end of the 1980s to 2010. Catena, 137, 256-268. http://dx.doi.org/10.1016/j.catena.2015.10.004

Wang, Z. Y., Wu, B., & Wang, G. (2007). Fluvial processes and morphological response in the Yellow and Weihe Rivers to closure and operation of Sanmenxia Dam. Geomorphology, 91(1-2), 65-79. http://dx.doi.org/10.1016/j.geomorph.2007.01.022

Wischmeier, W. H. & Smith D. D. (1978). Predicting rainfall erosion losses: guide to conservation planning. USDA, Agriculture Handbook, 537. U.S. Government Printing Office, Washington, DC.

Wongsa, S., & Shimizu, Y. (2001). Application of 1- and 2-Dimensional Coupled Hydrodynamic Model for Kushiro Marshland, *In Proceeding of 2nd IAHR Symposium on River, Coastal and Estuarine Morphodynamics*, pp. 831–840.

Zare, M., Panagopoulos, T., & Loures, L. (2017). Simulating the impacts of future land use change on soil erosion in the Kasilian watershed, Iran. Land Use Policy, 67, 558-572. http://dx.doi.org/10.1016/j.landusepol.2017.06.028

Zhang, L., O'Neill, A., & Lacy, S. (1995). Spatial analysis of soil erosion in catchment: a review of modeling approaches, International Congress on Modeling and simulation (MODSIM95), Water Resources and Ecology, 3, 58-64.

Zhang, X., Yan, G., Li, Q., Li, Z. L., Wan, H., and Guo, Z. (2006). Evaluating the fraction of vegetation cover based on NDVI spatial scale correction model. International Journal of Remote Sensing, 27(24), 5359-5372. DOI:10.1080/01431160600658107

Table.1. *P* factor values (Wischmeier and Smith, 1978).

Land use type	Slope (%)	*P* factor
Agricultural land	0-5	0.1
	5-10	0.12
	10-20	0.14
	20-30	0.19
	30-50	0.25
	50-100	0.33
Other	All	1.00

Figure 1: Map of Thailand and annual rainfall.

Figure 2. R factor map.

Figure 3. LS factor (A) and K factor (B) maps.

Figure 4. C factor (A) and P factor (B) maps.

Figure 5. Soil erosion map of Thailand using the RUSLE method.

Figure 6. Sediment capacity of each catchment (A) and a erosion and deposition map of Thailand (B).

Figure 7. Soil erosion and deposition map of the Chao Phraya River basin.

Figure 8. Soil erosion and sediment deposition map of the upper Mae Klong River basin.

Figure 9. Comparison between observed sediment data and the simulated sediment from the new technique (A) and the rating curve method (B). Comparison between the simulated sediments from the rating curve method and the new technique (C).

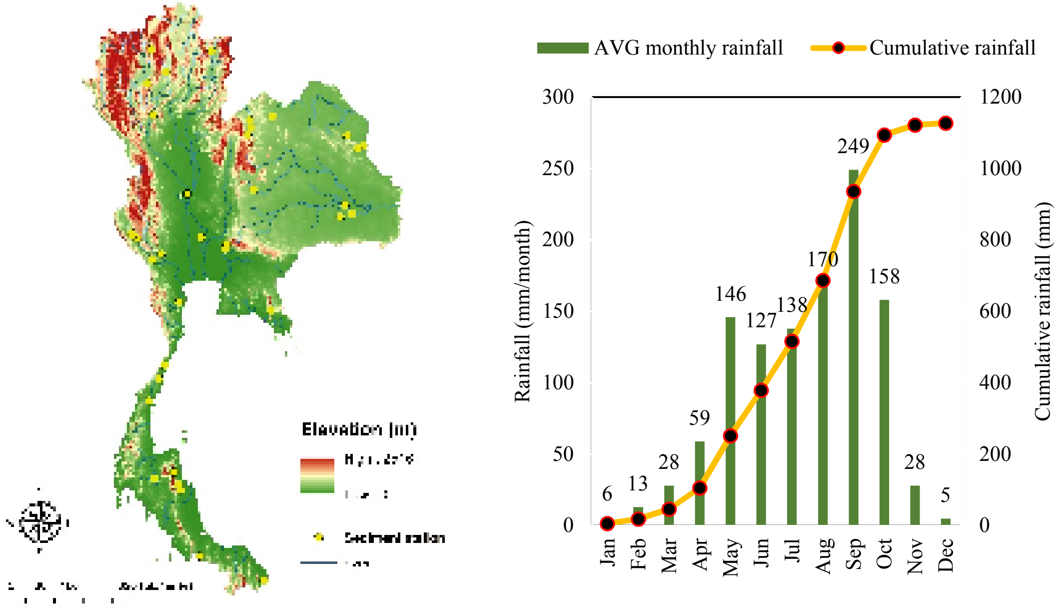

Figure 2: Map of Thailand and annual rainfall.

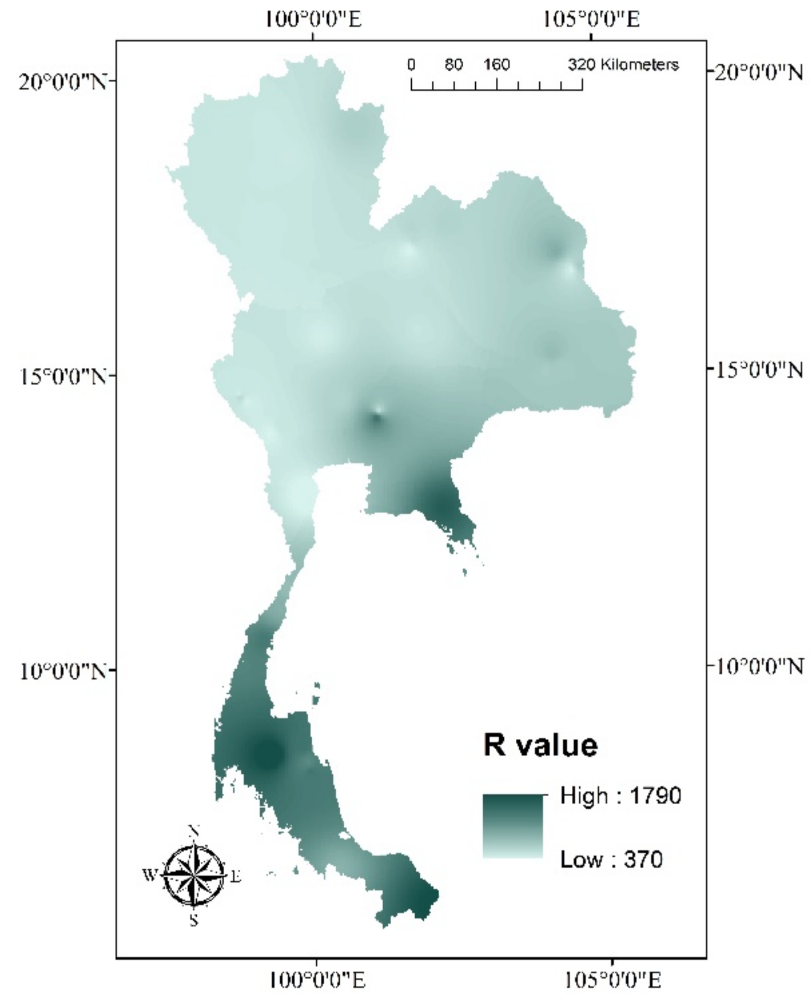

Figure 2. R factor map.

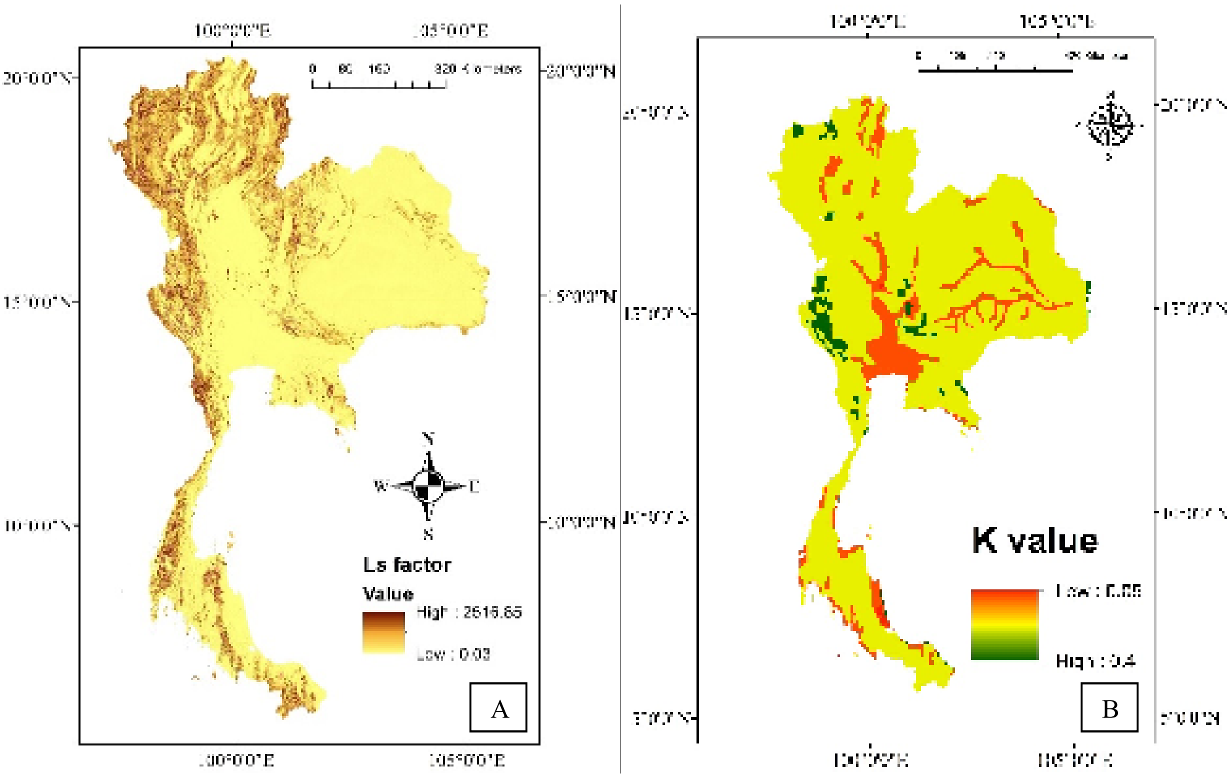

Figure 3. LS factor (A) and K factor (B) maps.

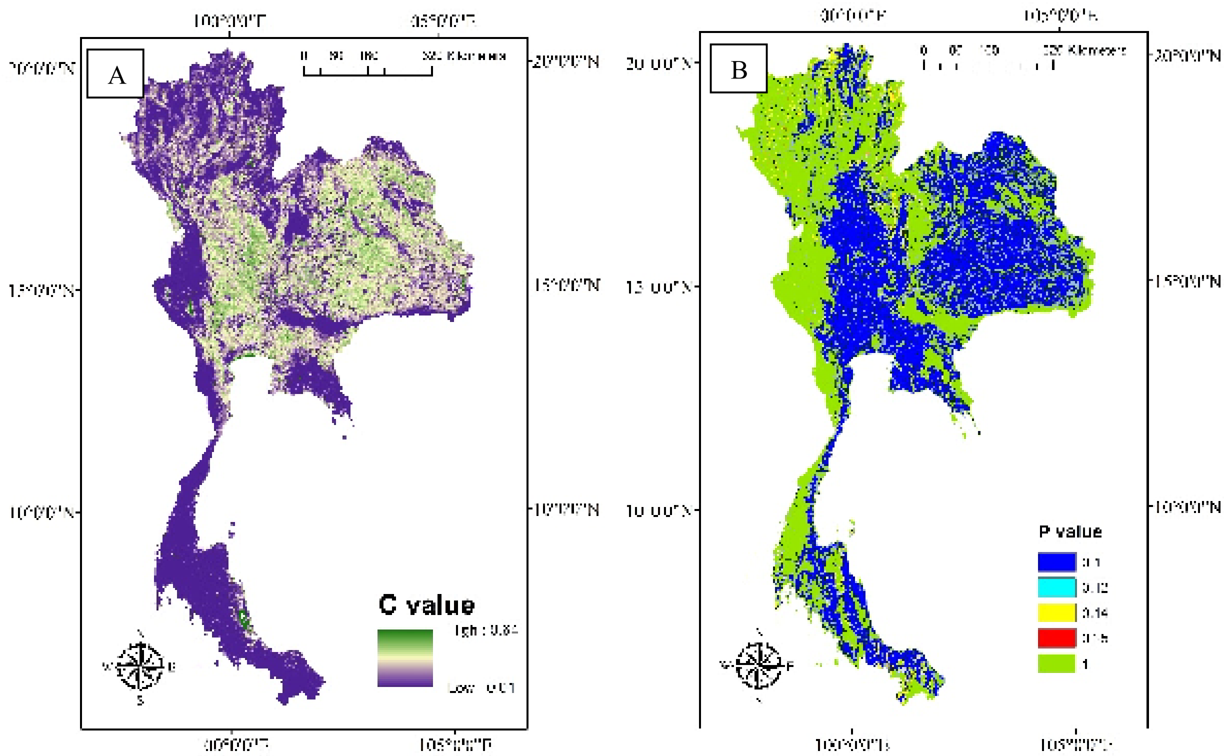

Figure 4. C factor (A) and P factor (B) maps.

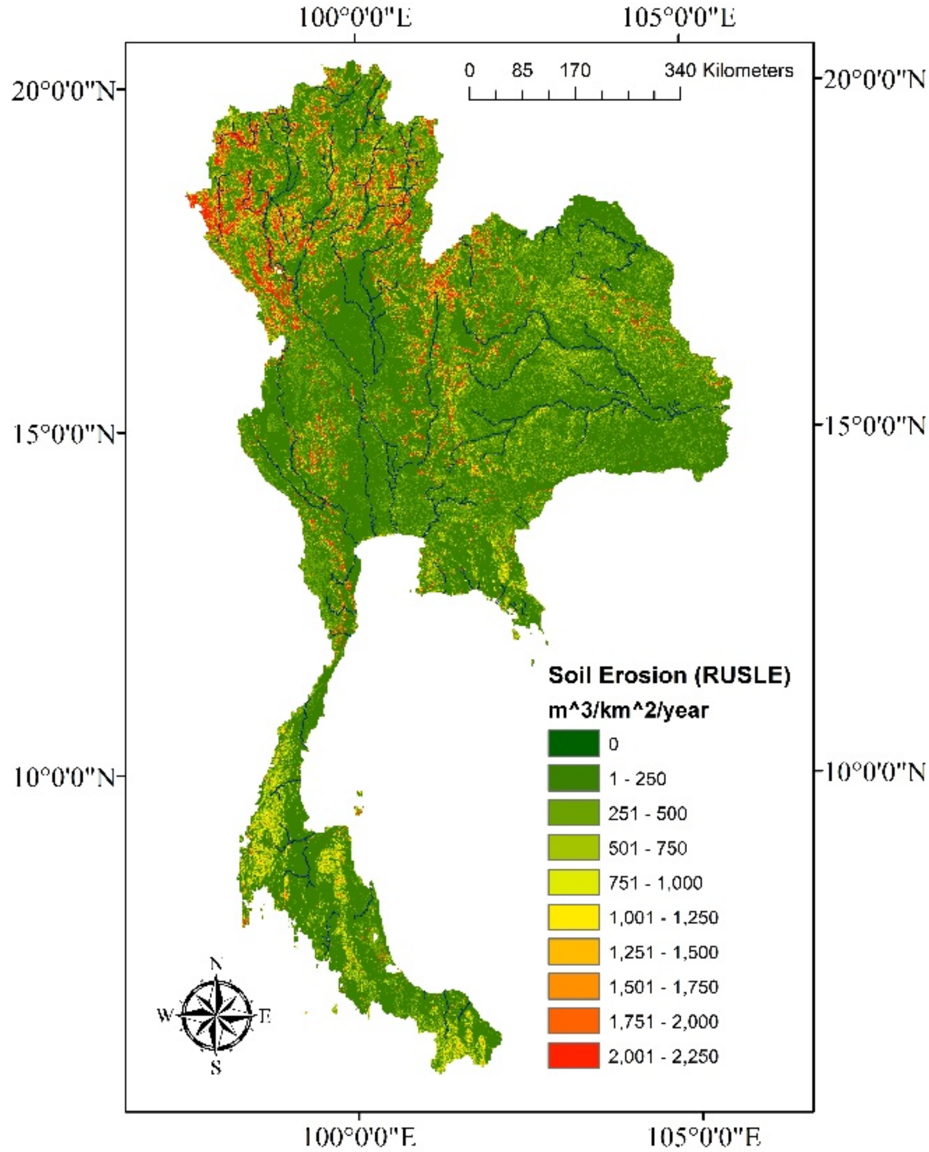

Figure 5. Soil erosion map of Thailand using the RUSLE method.

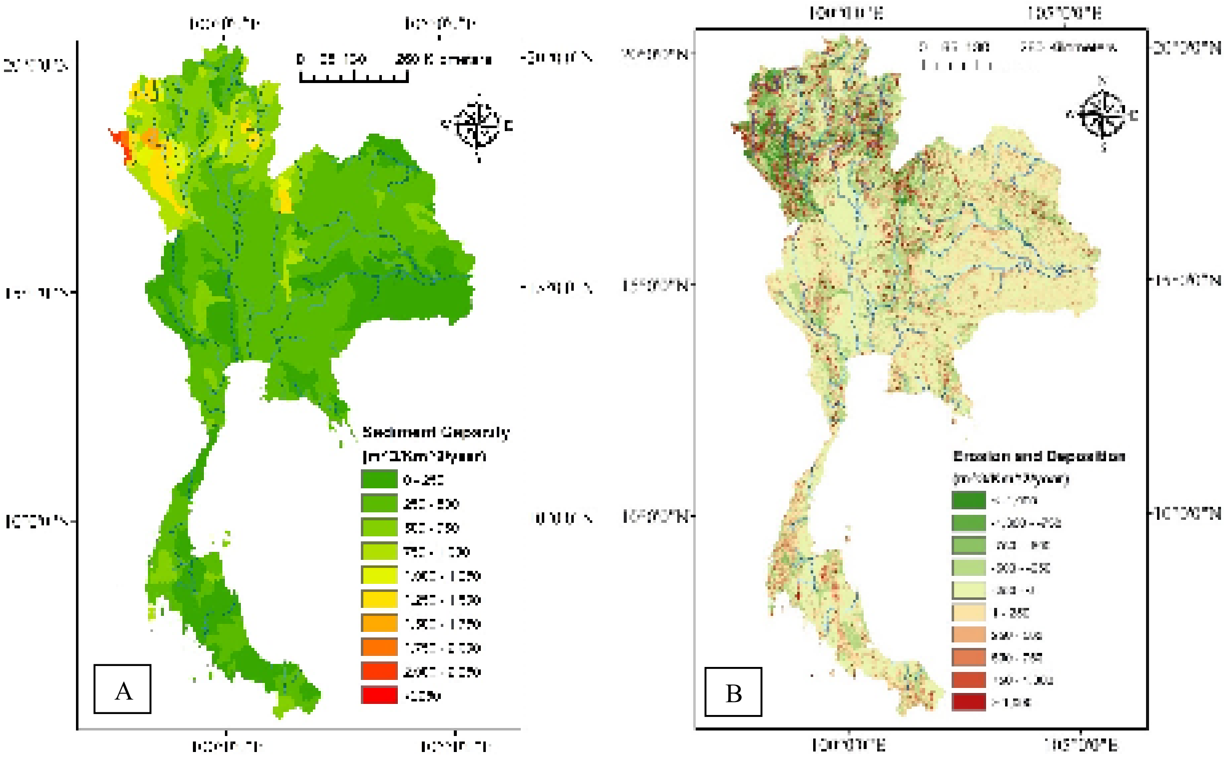

Figure 6. Sediment capacity of each catchment (A) and a erosion and deposition map of Thailand (B).

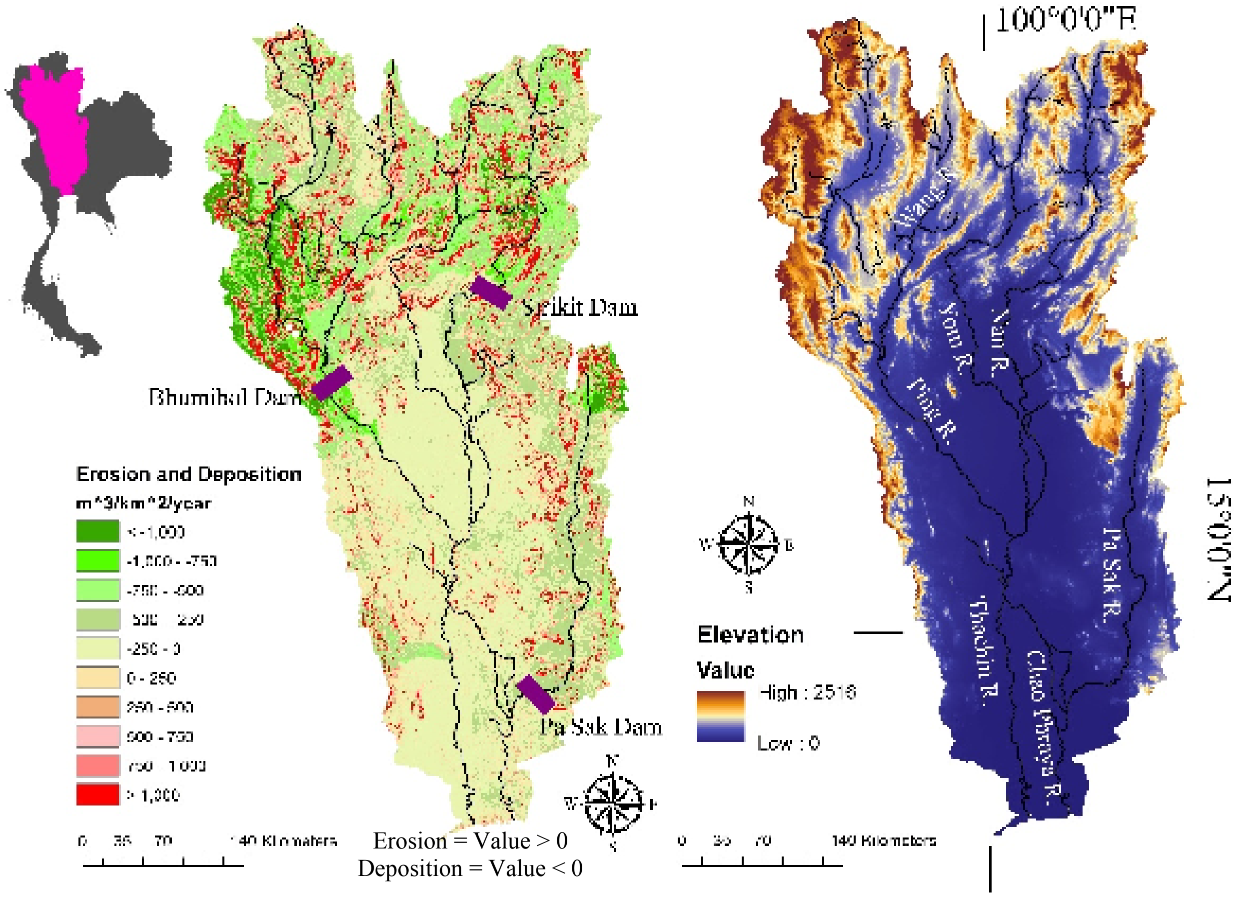

Figure 7. Soil erosion and deposition map of the Chao Phraya River basin.

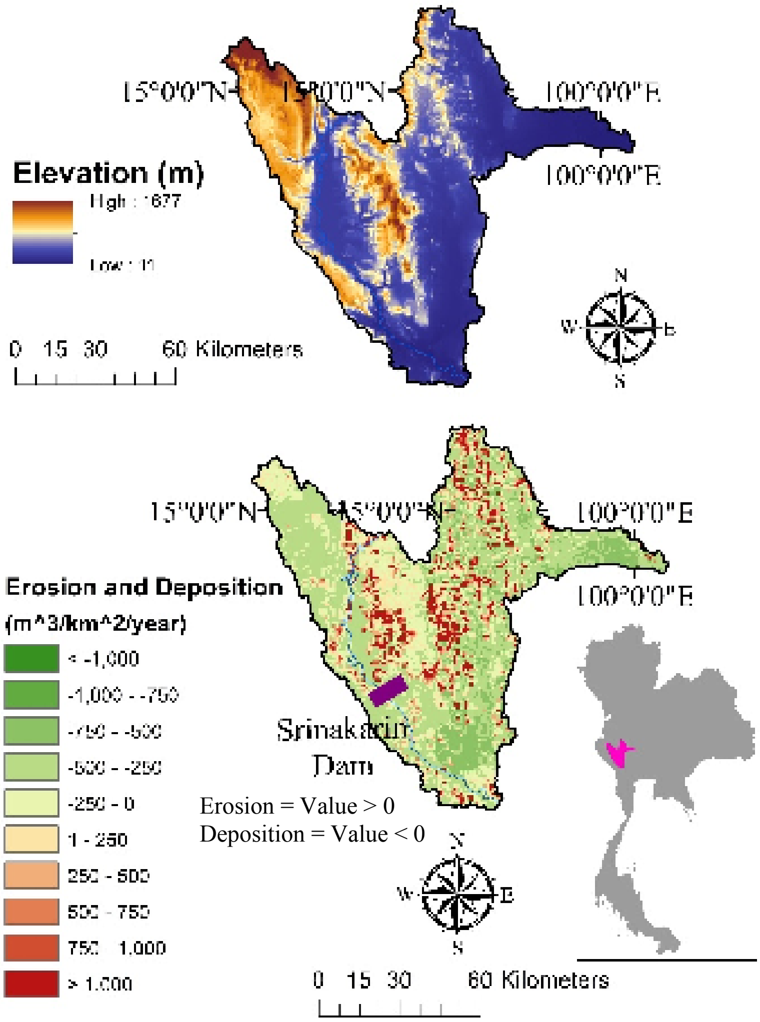

Figure 8. Soil erosion and sediment deposition map of the upper Mae Klong River basin.

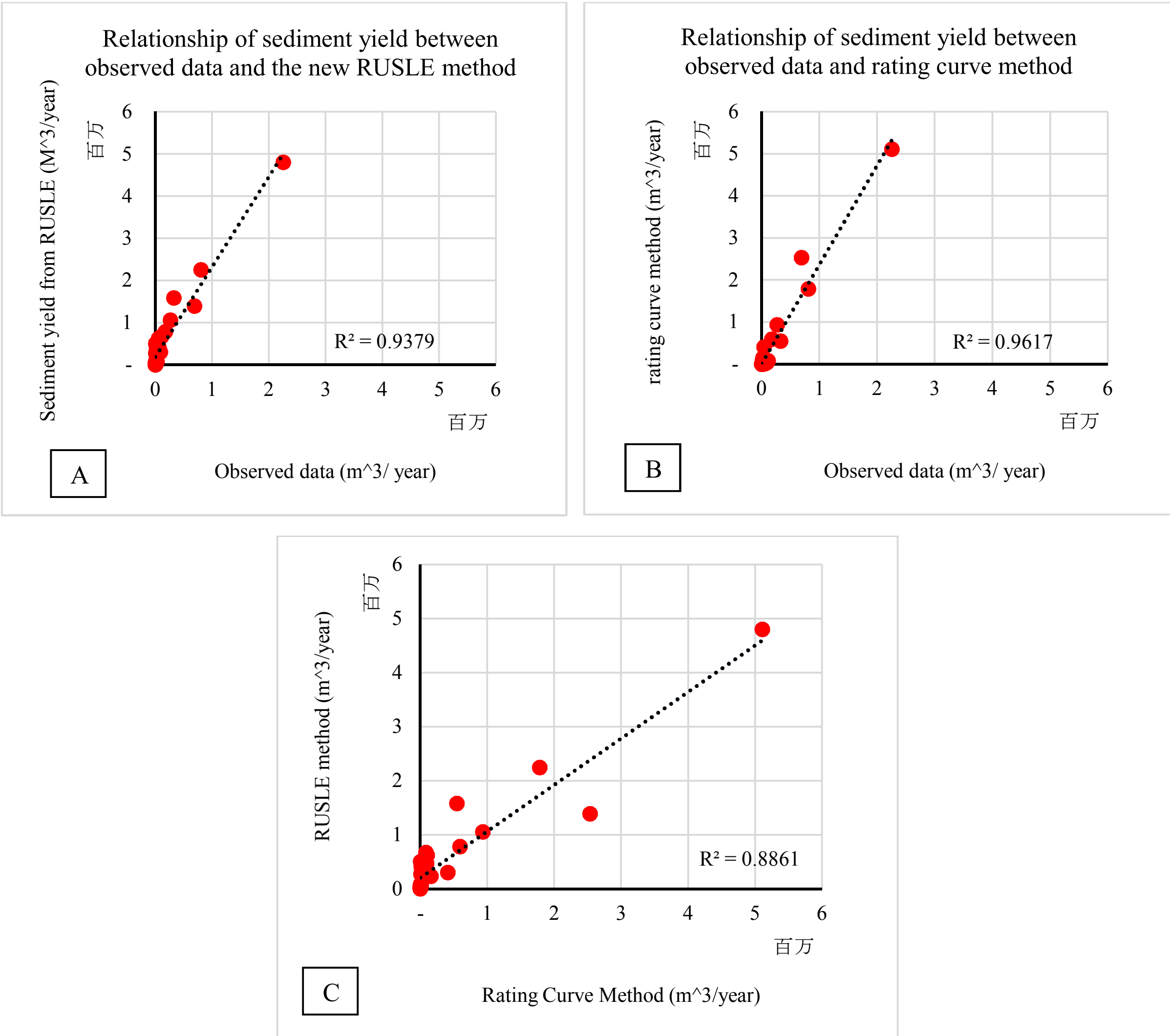

Figure 9. Comparison between observed sediment data and the simulated sediment from the new technique (A) and the rating curve method (B). Comparison between the simulated sediments from the rating curve method and the new technique (C).