SPATIALLY DISTRIBUTED MODEL FOR SOIL EROSION AND SEDIMENT TRANSPORT IN THE MEKONG RIVER BASIN

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ABSTRACT

Sedimentation is a global environmental problem that has critical impacts on irrigation, agriculture, navigation, fisheries and aquatic ecosystem. Then, such studies on sediment detachment, transport and deposition have attracted more attention recently. They have addressed the impact of human activities and climate change on sediment transport. However, only a few were reported in large river basins (e.g., drainage area >100 000 km^2). In this study, the Revised Universal Soil Loss Equation (RUSLE) was adopted in a GIS framework and coupled with a sediment accumulation and routing scheme to simulate suspended sediment load in the Mekong River basin. The developed model was applied to analyze sediment dynamics in large rivers. Suspended sediment load measured at nine gauging stations along Mekong River from 1990 to 2000 were compared with the model output.Thus, the results confirmed that the obtained soil erosion map in congruence with estimates of soil erosion and sediment load. Overall, the present model can be used to support river basin management to seek the best management practices in terms of erosion and sediment transport in the Mekong and other large rivers.

Keywords: Sediment, RUSLE, Sediment transport, Mekong River Basin, Soil erosion map

1. INTRODUCTION

Sediment erosion and transport are complex natural processed strongly affected by human activities such as deforestation, agriculture and urbanization. Erosion also leads to environmental damage through sedimentation, pollution and increased flooding. Although, soil erosion is a physical process with considerable variation globally in its severity and frequency, location and timing of erosion are also strongly influenced by social, economic, political and institutional factors. The costs associated with the movement and deposition of sediment in the landscape frequently outweigh those arising from the long-term loss of soil in eroding fields.

Nowadays, the The Mekong River is Asia's third largest river in terms of length and sediment load (Milliman and Meade, 1983). It receives enormous public attention in Asia because the river runs through six countries and approximately 60 million people dependent on the Mekong basin (Lal, 2005). The Mekong has recently been suffering from environmental degradation due to population increase, economic development, deforestation, and intensified meteorological extremes (Dudgeon, 2005). Especially, the dam construction and land use change within the basin are expected to alter the hydrological process and sediment transport (Le et al., 2007). Water-development projects, most

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notably construction of large hydropower dams, are important for economic development. Therefore, extensive plans are underway to build reservoirs in the tributaries as well as the mainstream areas within the riparian countries.The soil erosion in the Mekong River Basin (MRB) is mainly caused by rainfall and runoff, which is subjected to the type of land cover. Consequently, soil erosion patterns in the basin are heterogeneous and difficult to be modelled and predicted, particularly when data availability becomes a second constraint. Assessing the soil erosion involves diverse factors, especially due to the anthropologic activities. Soil conservation planning and erosion maps, typically created using erosion models, are becoming more and more important.

Among the models describing sediment yield and transport, empirical models, Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), and the revised version of it (RUSLE)(Renard and Freimund, 1994), have been widely applied to various spatial scales in different environments worldwide. Those empirical models are often criticized for employing unrealistic assumptions about the physics of the catchment system, ignoring the heterogeneity of the catchment inputs parameters and characteristics, such as rainfall and soil types, as well as ignoring the inherent non-linearity in the catchment system (Wheater et al., 1993). Nonetheless, RUSLE is generally the simplest and most widely applied, especially for large scale basins. They are particularly useful in identifying sources of sediment production.

The aim of this study was to estimate the soil erosion in the Mekong River basin by adapting an empirical model. A distributed Revised Universal Soil Loss Equation (RUSLE) formulation was used to simulate suspended sediment yield. The sediment yield was simulated over the 1990 to 2000 period, thus covering different climatic and land use covers. Then, the distributed RUSLE equation formulation was integrated to a river network routing scheme to analyse the monthly change of suspended sediment load at nine stream gauging stations. Overall, the results presented in this study can provide decision support for river basin managers about where the best management practices can be implemented effective and low cost.

2. TARGET RIVER BASIN

The present study focus on the Mekong River basin, which covers an area of approximately 795,000 km2 Figure 1. The basin consists of approximately 33 % of the forests. Among major rivers of the world, the Mekong ranks 12th with respect to length (4880 km), 21st with respect to catchment area. The wet season lasts from May to October when the average rainfall around 80-90% of the annual total. The dry season period starts from November and lasts until April. The minimum annual rainfall is 1000 mm/year (NE of Thailand) and the maximum is 4000 mm/year (West of Vietnam).

The Mekong is the largest trans-boundary river in Asia. It originated in Tibet in China and flows down to Southern Vietnam, a distance of more than 4600 km. The Mekong River Basin is populated with approximately 60 million people and is considered to be one of the most culturally diverse regions of the world. Agriculture, fishing and forestry provide employment for approximately 85% of the basin's residents. In this basin, Acrisols were found the dominant soil type, which are tropical soils that have a high clay accumulation in a horizon and are extremely weathered and leached. Their characteristics include low fertility and high susceptibility to erosion if used for arable cultivation (FAO, 2006). The rest of the areas are mixtures of deciduous and evergreen covers as well as woodland and shrubland with some undisturbed forest land.

This study focuses on the Mekong river basin, examining soil erosion and sediment records specifically from the following hydrologic station; Chiang Saen (002), Luang Prabang (003), Vientiane (004), Nakhon Phanom (005), Khong Chiam (007), Pakse (008), Kratie (009), Kampong Cham (010) and Phnom Penh (011).

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3. METHOD

3.1 Soil Erosion Model

The Universal Soil Loss Equation (USLE)(Wischmeier and Smith, 1978), and the revised version of it, named RUSLE (Renard and Freimund, 1994)were developed to predict the long term average annual erosion, *A*, from field size areas. In this study, the RUSLE approach was applied in a distributed manner, using a 3.6 km resolution GIS which makes spatial soil erosion assessment feasible with a reasonable accuracy in large areas.

The RUSLE basic equation includes six factors: R the rainfall-runoff erosivity factor, K the soil erodibility factor, L the slope length factor, S the slope gradient factor, C the crop and management factor and P the conservation support practice factor. The RUSLE model is often represented by the equation:

$$A = R\ K\ LS\ C \tag{1}$$

Where:

A is average soil loss per unit area during a unit period of time, usually one year (tons ha^{-1} $year^{-1}$),

R is average rainfall and runoff factor, the erosion potential of rainstorms (MJ ha^{-1} mm h^{-1}).

For this study, the threshold-type equation of Loureiro and Coutinho is adopted:(2001)

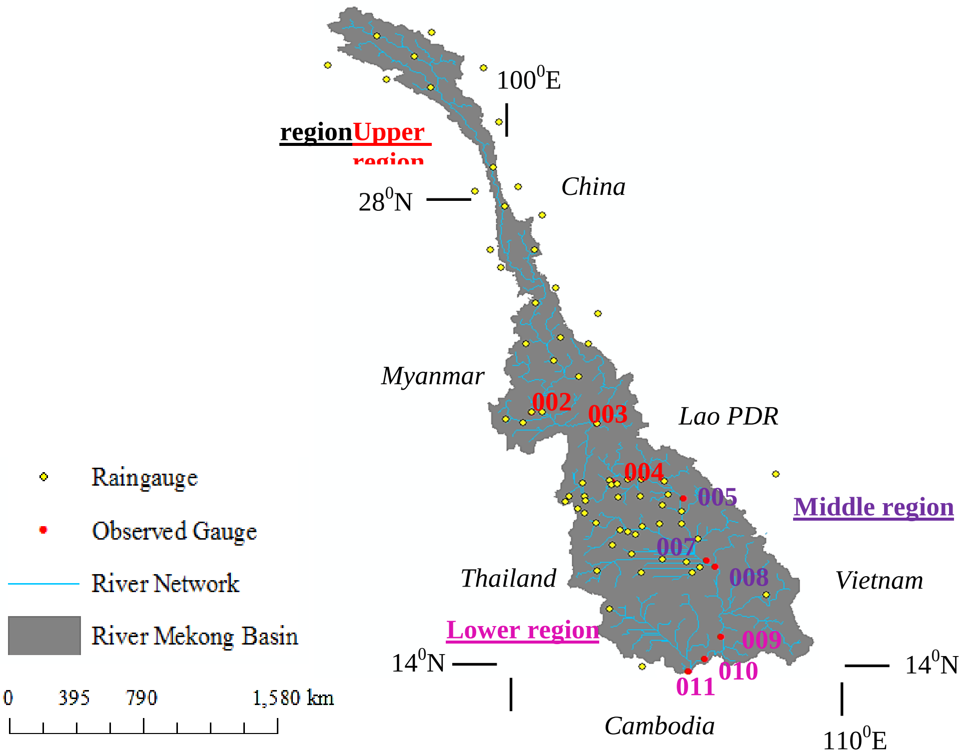

Fig. 1. The Mekong River basin

$$R = \sum_{i=1}^{N} \sum_{j=1}^{12} (7.05\ rain_{10} - 88.92\ days_{10})_{i,j} \tag{2}$$

Where N is the number of observation years, rain10 is monthly rainfall intensity, when it is≥ 10mm, otherwise it is set to zero, day10 is the monthly number of days with rainfall ≥ 10 mm. Eq. (2) gives a higher erosion potential of rainfall with higher monthly rainfall, $rain_{10}$. It also accounts for the fact that, for a given rainfall amount, the lower are the rainy days $days_{10}$, the higher is the rainfall intensity

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and erosion potential, as expected. Using the above equation the monthly R factor value for rain gauges of the Mekong river basin were computed and the resulting average annual R factor, interpolated with Inverse Distance Weighted Interpolation (IDW) method found in the ArcGIS Spatial Analyst tool to make the same resolution or grid cell size as the other maps inserted in the ArcGIS for the period 1990 – 2000, is shown in Figure 2 (a).

K is the average soil erodibility factor (tons MJ-1 h mm-1). Some soil types are naturally more prone to soil erosion due to their physical structure. Erodibility is a function of soil texture, organic matter content and permeability. In this study, to estimate the K factor, the soil-erodibility nomograph Wischmeier using measurable properties are used. The soil erodibility nomograph comprises five soil profile parameters: % of modified silt (0.002-0.1mm), % of modified sand (0.1-2mm), percent of organic matter (OM), class of soil structure (s) and permeability (p). The Mekong river basin digital soil map, 2005 raster file was obtained from the FAO. After the soil map was added as a layer in ArcGIS, the soil map attribute table was edited by adding a new field of K values under the Edit menu at attribute view before K factor map were produced. Figure 2 (b) shows the K factor map. In this study, the K factor values range is between 0.02 and 0.22. This value is not very high variability, and may be due to the homogeneity of soil types and characteristics.

C is the cropping, vegetation and management factor which represents the effect of vegetation and management on the soil erosion rates and it ranges between 0 and 1. The values of C were adopted from IGBP based on the land cover. The land cover of the River Mekong Basin is classified with six land cover classifications: Water, Urban, Wetland, Forest, Crop field, and grassland. C factors were generated as the same way as the K factor by auditing the attribute table. The C factor map produces since 2005 is shown in Figure 2 (c). In this study, C factor for Mekong basin is between 0.0001 to 0.765.

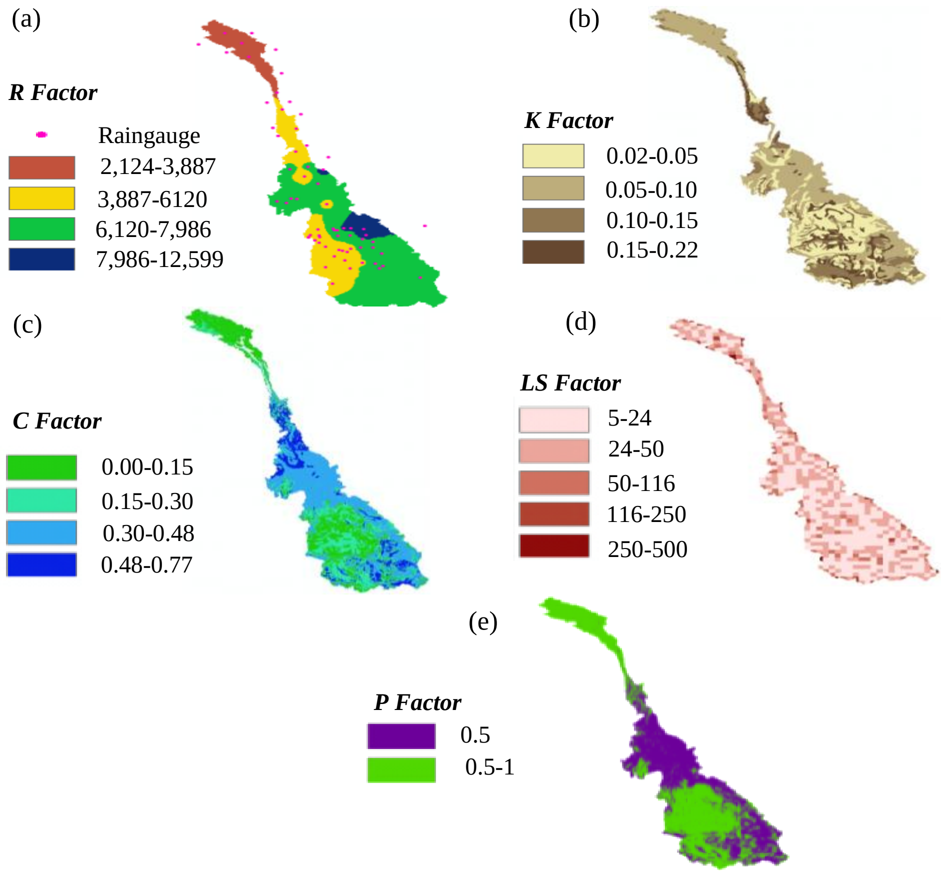

Fig. 2. Distribution erosion factors for Mekong. (a) Rainfall erosivity factor 'R', (b) Soil erodibility factor 'K' (c) Slope steepness factor 'S', (d) Cover management factor 'C ' (e) Support practice factor 'P'

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LS are the slope length and the slope gradient factor. The slope has a major effect on the rates of soil erosion. The higher the slope, the higher is the velocity of overland flow, thus increasing the shear stresses on the soil particles. Slope steepness (%) is directly derived from the digital elevation model (DEM). It represents the surface terrain of the catchment and permits to retrieve geographical information. In this study, the DEM of the Mekong River basin was built from GTOPO30 with spatial resolution of ~ 20 km2 (grid area: 2 × 2 min). Length Slope factor map, Figure 2 (d) was generated using Surface Analysis under Spatial Analysis function and raster calculation in ArcGIS.

P is a supporting practice factor. It reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduces the amount of erosion, the higher the supporting practice, the lower the value of the P factor. It is the ratio of soil loss with a specific support practice on croplands to the corresponding loss with upslope and downslope tillage. In this study, P factor, Figure 2 (e), ranges from 1.0 to 0.5.

This study relies on historical data published by the Secretariat of the Mekong River Commission (MRC 2009). In this study, for hydrological data, rainfall data from the year 1990 to 2000 periods from 65 rainfall stations located along the Mekong river basin and its tributaries were used. Moreover, annual records of discharge and suspended sediment concentration (SSC) from 1990 to 2000 was extracted from six gauging stations located along the Mekong river basin. Flow and SSC records from six gauging stations located on the main stream of Mekong basin were used for this study to calculate the sediment load. The stations were selected based on two main criteria: first their relative location from one another, and second, the completeness of flow and sediment records for the station.

In order to calculate the soil erosion, the RUSLE equation (1) was used to calculate the annual average soil loss rate (A) in ton/ha/year. In order to predict the annual average soil loss rate in the Mekong river basin, the R, K, LS, C and P factors from the earlier were multiplied using the raster calculator function tool of ArcGIS.

3.2 Sediment Transport

The resulting mean annual soil losses evaluated with the RUSLE model are shown in Figure 3. In particular, soil losses were computed on a monthly basis and then were accumulated across a channel network extracted from a 3.6-km resolution DEM uses the standard D8 flow direction method (O'Callaghan and Mark, 1984). In addition, in this model we assume that no deposition process along the river reach was assumed. The resulting river network is in a good agreement with the observed. The accumulated monthly sediment production Sk expressed in tons/month, in each basin upstream nine measurement stations (k = 1,…, k = 9) are then routed through the channel network with a conceptual, lumped scheme, aiming at reproducing the dominant mode of behavior of the sediment transport process (Moore, 1984). For the sediment movement function a reasonable assumption is that the travel time of sediments in the basin is a random variable with exponential distribution, with mean travel time θk, expressed in days and estimated as the ratio of a length scale, Lk, and of a velocity scale, V.

The length scale is assumed as a power law function of each basin area, Ak, according to the Hack's law, L = 1.4 A0.6, with L being the mainstream length expressed in kilometers and the area A in km2 (Hack, 1957; Rigon et al., 1996).

Assuming each kth basin as a storage, feeded by sediments detached from its hillslopes at a constant rate Sk during each month and releasing a sediment discharge qs,k(t) at its outlet, in the above assumption the sediment stored in the basin W(t) is proportional to qs,k(t):

$$W_k(t) = \theta_k q_{s,k}(t) \quad (3)$$

And the of mass conservation for sediments at the basin scale become scale becomes the differential equation of a linear reservoir:

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$$dW_k(t)/dt = \theta_k dq_{s,k}(t)/dt = S_k - q_{s,k}(t) \quad (4)$$

Which can be solved given the initial condition $q_{s,k}(t = 0) = q_{s,0,k}$.

In this conceptual and lumped modelling framework, the monthly suspended sediment discharge qs,k (tons/month) at each kth basin's gauging station at each month, with duration of T results as (Roberto et al., 2012):

$$q_{s,k} = q_{s,k} e^{-T/\theta_k} + S_{k,i}\left(1 - e^{-T/\theta_k}\right)\text{(tons/month)} \quad (5)$$

And the monthly sediment yield is:

$$V_{s,k} = q_{s,k}\theta_k(1 - e^{-T/\theta_k}) + S_k T + S_k\theta_k\left(e^{-T/\theta_k} - 1\right)\text{(tons).} \quad (6)$$

The optimal value of the mean sediment transport velocity, the calibrated parameter, was estimated as V = 0.5 m/s by minimizing, as objective function, the mean inter-basin Nash-Sutcliffe efficiency coefficient, NS, of the simulated vs. observed monthly sediment yield which resulted NS = 0.623.

4. RESULTS AND DISCUSSIONS

4.1 Average Soil Erosion

The resulting means of annually soil erosion evaluated with the RUSLE model are shown in Figure 3 The soil loss over the LMB area is calculated using Eq. (1). Figure 3 shows the spatial pattern of soil loss categories by five ranges of soil loss value. Three qualitative categories have been chosen for the output soil erosion classes: low (soil loss range, 0.0-2.649 ton ha-1 yr-1) , moderate (soil loss range, 2.649-14.128 ton ha-1 yr-1), and high soil erosion (soil loss range, 14.128-32.167 ton ha-1 yr-1). The result shows that, moderate classes are scattered in all over the Mekong basin area. The moderate class is occupying 79% of the study area in correspondence to low steepness slope, range from 0 to 5.98%. These types of soils are sand and clay, have better permeability and highly resistant to runoff impact. The moderate class erosion also is related mainly to the protective role of forest and natural vegetation cover. The Low class in this study area is occupying 14% in the lower region and some part in the upper region. While, the High class occupying 7% in this study scattered in the middle region near Vietnam and also there are some part near Myanmar and Lao PDR. This is can be expected due to cropland cover and higher average annual rainfall distribution. Furthermore, type of soil is highly silt contents and sand, easy to detach due to runoff. In this case, the combination of the different factors classifying the soil erosion gives a good prediction of potential area.

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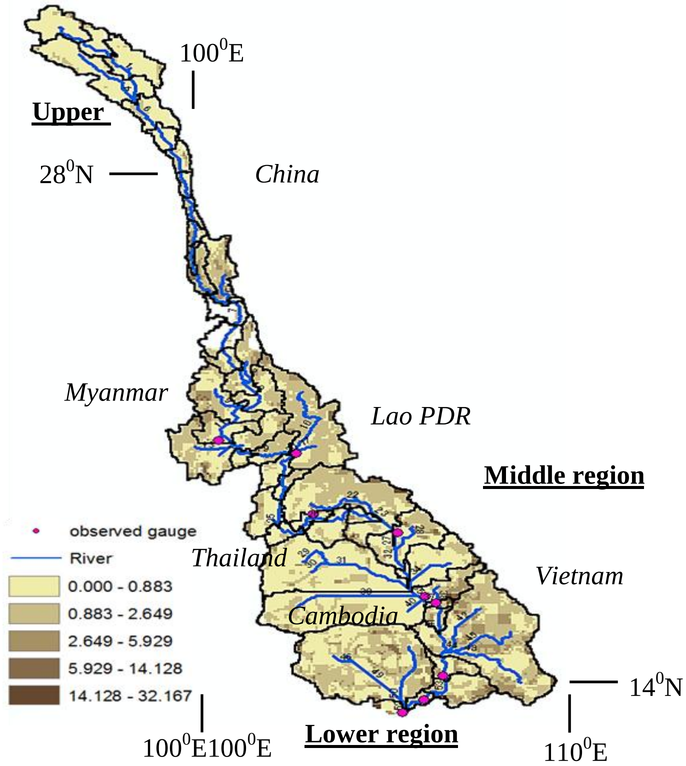

Fig. 3. Average soil loss (ton ha^{-1} yr^{-1})

4.2 Suspended Sediment Load Changes

The annual sediment loads of the Mekong River were relatively stable in the past 40 years (Walling, 2008). However, there is a significant seasonal change in the annual sediment loads among the year seasons. Changes in sediment loads of the LMB have been analysed relying on the existing sediment data in many literatures (Fu et al., 2006; Kummu and Varis, 2007; Lu and Siew, 2006; Walling, 2008; Walling, 2009; Wang et al., 2011). Since the existing sediment data in the MRB have been collected by inconsistent method and had a low sampling frequency (Wang et al., 2011) studies reported different changing trends on sediment load in MRB. The sediment data obtained by Total Suspended Solids (TSS) are likely to underestimate the true mean concentration in the river section and this is why several studies (Fu et al., 2006; Kummu and Varis, 2007; Lu and Siew, 2006) had concluded that a sharp reduction in the sediment load at Chiang Sean caused by Manwan hydropower. The simulation results were used to investigate the temporal change in suspended sediment load at upper, middle and lower monitoring stations cases from 1999 – 2000, Figures 4a, b, c, respectively. The linear correlation coefficient between simulated and observed values was in the range of 0.55–0.96, 0.82–0.98, and 0.88–0.95 for the upper, middle and lower stations, respectively. While, the mean Nash-Sutcliffe efficiency result for the upper stations was 0.526, for the middle stations were 0.717 and for the lower stations was 0.628. Although, the model simulation was mean relative error 41% underestimated, the seasonal sediment load was fairly well simulated at the nine stations.

Based on simulation, Figure 4 shows that the sediment load of summer season was the highest in the upper region with 9.93 ×10-6tons/month sediment discharge. While, the sediment load of the autumn season was 2.0 ×10-7tons/month and 2.59 ×10-7tons/month in the middle and lower regions, respectively, which were the highest, compared to the other seasons. The lowest sediment load was estimated in the winter season in the three regions. The sediment load was 1.39 ×10-5, 6725 and 1.6 ×10-5tons/month for the upper, middle, lower regions, respectively. The result also reveals an increasing trend in sediment load along the three regions for the four investigated seasons. These results show that the suspended sediment load was higher in the rainy season (summer and autumn) than the dry season (winter). That is due to the intensive soil erosion coincident with heavier precipitation. Moreover, the topographic decrease can cause to the decrease in the main stream water velocity, which increase the sediment deposition. However, the sediment load increased due to this

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deposition process. Thus, the sediment load in the upper-middle region of the Mekong River was lower than the lower region.

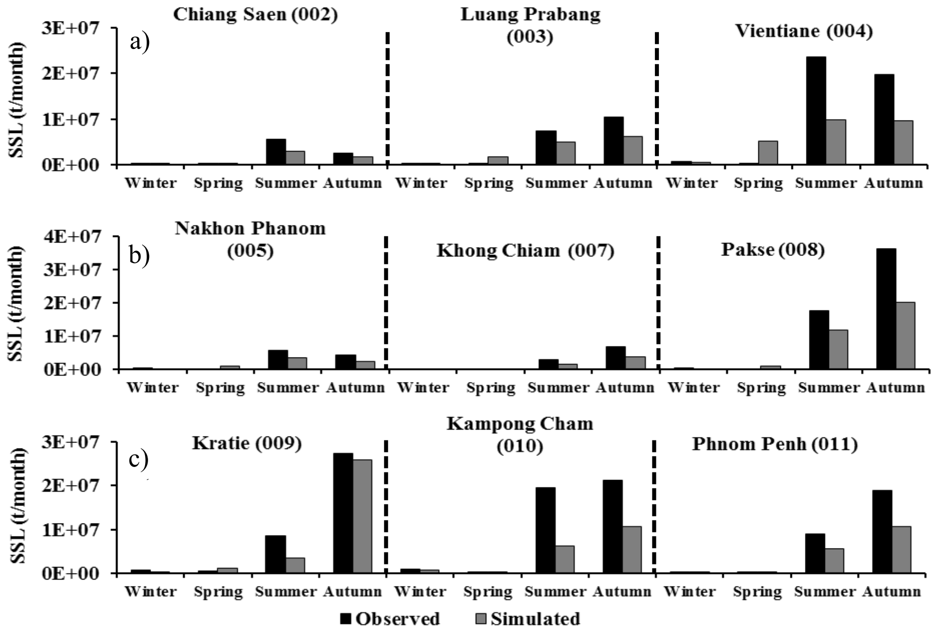

Fig. 4.Seasonal change in the average SSL (a) upper region stations; (b) middle region stations; (c) lower region stations.

5. CONCLUSIONS

A conceptual modelling framework based on monthly precipitation data, distributed GIS information, RUSLE-based was developed to estimate surface erosion and sediment transfer scheme. This approach provides a reasonable solution to model sediment load in the Mekong River basin, taking into account in a proper way land use management practices. Then the RUSLE model was integrated to a river networking, routing scheme, which assumes an exponential distribution of sediment travel time with a geomorphology derived time scale, to evaluate the soil loss.

The results provide the spatial distribution of soil erosion over the Mekong River basin. Soil erosion was the highest close to Vientiane and Nakhon Phanom due to highest annual rainfall records around this area. This can help us to identify the severe soil erosion areas which deserve priority attention in basin management for soil and water conservation.

The sediment load was estimated to be 90% higher in the rainy seasons (mean 3.475 ×106 tons/month) than the dry seasons.

The sediment load in the lower region Mekong River basin showed an increase due to accumulation process.

The approach introduced here shows the suitability of identifying the severe soil erosion and assessment sediment load at large basin scales like the Mekong. Thus, it can be applied not only for the Mekong but also for other large basins since the available data of soil erosion and suspended sediment is important in the assessment of changes and trends on sediment load in the river basin.

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REFERENCES

[1]. FAO (2006) Guidelines for soil description, FAO Rome, pp.110.

[2]. Fu K.D., He D.M. and Li S.J. (2006) Response of Downstream Sediment to Water Resource Development in Mainstream of the Lancang River. Chinese Science Bulletin 51 (Suppl.), pp.119–126.

[3]. Dudgeon, D. (2005) River management for conservation of freshwater biodiversity in monsoonalAsia. Ecology and Society 10(2),15.

[4]. Hack, J. (1957) Studies of Longitudinal Stream Profiles in Virginia and Maryland. US Geological Survey Professional Paper, 294-B.

[5]. Lal, R. (2005) Soil Erosion, Soil and Water Conservation Society, Ankeny, IowA, 340 p.

[6]. Le, T. V. H., Nguyen, H. N., Wolanski, E., Tran T.C., and Haruyama, S. (2007) The Combined Impact on the flooding in Vietnam's Mekong River Delta of Local Man-made Structures, Sea Level Rise, and Dams Upstream in the River Catchment. Estuarine, Coastal and Shelf Science, 1(1–2), 110–116.

[7]. Loureiro, N.S. and Coutinho M.A. (2001) A new procedure to estimate the RUSLE El30 index, based on monthly rainfall data and applied to the Algarve region Portugal. J. Hydrol. 250, pp.12–18.

[8]. Kummu, M. and Varis, O. (2007) Sediment-related Impacts Due to Upstream Reservoir Trapping, the Lower Mekong River. Geomorphology 85, pp.275–293.

[9]. Lu, X. X., and Sie, R. Y. (2006) Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. Hydrol. Earth Syst. Sci., 10, pp 181-195.

[10]. Milliman, J. D., and Meade, R. H.(1983) World-wide delivery of river sediment to the oceans. Jour. Geology, v. 91, p. 1-21.

[11]. Moore, R.J. (1984) A dynamic model of basin sediment yield. Water Resour. Res. 20 (1), 89–103.

[12]. MRC (2009) Mekong River Commision for Sustainable Development: About the Mekong, water at work. Mekong River Commision, Vientiane, Lao PDR.

[13]. O'Callaghan, J. and Mark, D.M. (1984) The extraction of drainage networks from digital elevation data. Comput. Vision, Graphics, Image Process. 28 (3), 323–344.

[14]. Renard, K.G., Freimund, J.R. (1994) Using monthly precipitation data to estimate the R-factor in the revised USLE. J. Hydro. 157, pp. 287-306.

[15]. Rigon, R., Rodriguez-iturbe, I., Maritan, A., Giacometti, A., Tarboton, D.G. and Rinaldo, A. (1996) On Hack's law. Water Resour. Res. 32 (11), 3367–3374.

[16]. Roberto, R., Thanh H., Maria C. (2012) A RUSLE approach to model suspended sediment

Received July 2013, Accepted Dec. 2013

load in the Lo river (Vietnam): effects of reservoirs and land use changes. J. Hydrol. 422-423, pp 17-29.

[17]. Walling, D.E. (2008) The Changing Sediment Load of the Mekong River. AMBIO: A Journal of the Human Environment 37(3), pp.150–157.

[18]. Walling, D.E. (2009) Chapter 6 The Sediment Load of the Mekong River. In: The Mekong: Biophysical Environment of an International River Basin, Ian C. Campbell Eds. New York: Elsevier Inc., pp. 113-142.

[19]. Wang, J. J., Lu, X. X., and Kummu, M. (2011) Sediment load setimates and variations in the lower Mekong River. River Res. Appl., 27, pp 33-46.

[20]. Wheater, H. S., Jakeman, A. J., and Beven, K. J. (1993) Progress and Directions in Rainfall-runoff Modelling. In: Jakeman, A. J., Beck, M. B., McAleer, M. J. (Eds.), Modelling Change in Environmental Systems. John Wiley and Sons, Chichester, pp. 101-132.

[21]. Wischmeier, W. and Smith, D. (1978) Predicting Rainfall Erosion Losses- A Guide to Conservation Planning.U.S. Department of Agriculture Handbook No.537.

Received July 2013, Accepted Dec. 2013