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DISTRIBUTED MODEL OF HYDROLOGICAL AND SEDIMENT TRANSPORT PROCESS IN MEKONG RIVER BASIN

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ABSTRACT: Soil erosion and sediment transport have been modeled at several spatial and temporal scales, yet few models have been reported for large river basins (e.g., drainage areas > 100,000 km^2). In this study, we propose a process-based distributed model for assessment of sediment transport at a large basin scale. A distributed hydrological model was coupled with a process-based distributed sediment transport model describing soil erosion and sedimentary processes at hillslope units and channels. The model was tested in Mekong River Basin (795,000 km^2). The simulation over 10 years showed good agreement with the observed suspended sediment load in the basin. The average Nash–Sutcliffe efficiency (NSE) and average correlation coefficient (r) between the simulated and observed suspended sediment loads were 0.60 and 0.78 respectively. Sensitivity analysis indicated that the suspended sediment load is sensitive to soil detachability over land (K_f) in the Mekong River Basin. Overall, the results suggest that the present model can be used to understand and simulate erosion and sediment transport in large river basins such as Mekong River Basin.

Keywords: Soil erosion, Sediment transport, Hydrological model, Mekong river basin

1. INTRODUCTION

Sediment erosion, transport and deposition are complex natural processed strongly affected by human activities and leads to environmental damage through sedimentation, pollution and increased flooding. The sediment produced by soil erosion process is transported into rivers, reservoirs and ponds resulting in high sediment deposition rates and frequent dredging operations. Effective management of sediment in rivers is becoming increasingly important from an economic, social and environmental perspective. Sediment dynamics in a river basin can be estimate both quantitatively and consistently by using modeling tools [1]. Currently, there are many models was developed for a wide range of applications, over a range of scales from the plot based models to basin scale approaches for erosion and sediment transport. Basin scale process-based distributed approach is advantageous for modeling sediment delivery processes since eroded sediments are produced from different sources throughout a basin.

Despite of the fact that many of process-based sediment transport models have been developed over the past four decades, such as Water Erosion Prediction Project (WEPP) [2], European Soil Erosion Model (EUROSEM) [3] and Areal Non-point Sources Watershed Environment Response Simulation (ANSWER) [4], the application of these models to large basin scales (e.g drainage area > 100 000 km^2) remained questionable. While to address the problem, in this study we primarily consider the large basin scale in developing the process-based sediment transport model. Besides, some existing models application at these scale have borrowed heavily from smaller scale application. The existing models are either in-stream models, land surface models or, in some cases, have both land surface and in-river components. Basin scale prediction of sediment generation and transport requires consideration of land surface processes and in-river processes. The objectives of this study to check the feasibility of developed process-based model on simulating of sediment dynamic considering hillslope sediment and sediment in river system separately. The model was developed by integrating soil erosion-sediment transport process with the distributed hydrological model to estimate the soil erosion, deposition, transport and sediment yield in large river basin. The model has been calibrated and validate for Mekong River basin.

2. STUDY AREA

The present study focused the Mekong River basin, which covers an area of approximately 795,000 km^2 (Fig.1). The basin consists of approximately 33 % of forests. Among major rivers of the world, the Mekong ranks 12th with respect to length (4880 km), 21st with respect to catchment's 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 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. The rest of the areas are mixtures of deciduous and evergreen covers as well as woodland and shrubland with some undisturbed forest land.

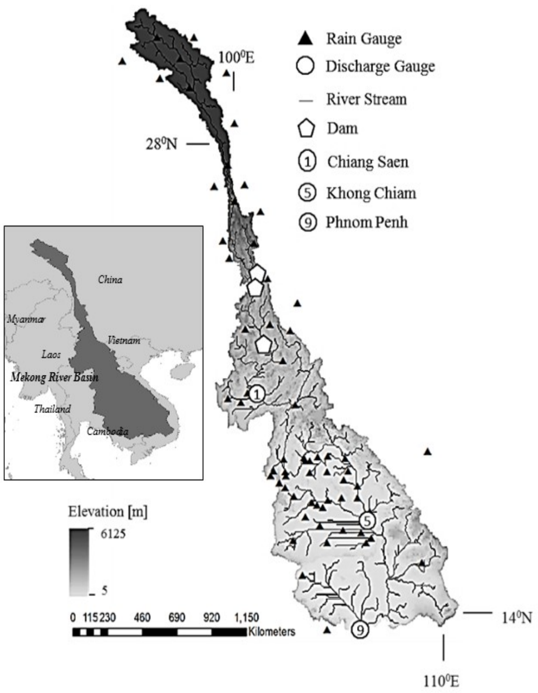

Fig.1 Mekong river basin map.

3. METHODOLOGY

The important sediment dynamics (soil erosion, sediment transport and deposition) were modelled and integrated with a process-based distributed hydrological model (DHM). In sediment module, sediment dynamics on hillslope and river was modelled separately and linked to each other systematically.

3.1 Hydrological Modelling

The distributed hydrological model used in this study is a geomorphology based hydrological model (GBHM) developed at the University of Tokyo [5]. It solves the continuity, momentum and energy equations using two modules; hillslope model and river routing model. The GBHM uses a basin subdivision scheme, a sub grid parameterization scheme, a physically based hillslope hydrological simulation, and a kinematic wave flow routing in river network [6]. Further details can be described as in [5].

3.2 Process based soil erosion and sediment transport model

3.2.1 Hillslope erosion process

Hillslope erosion is divided into two systems; detachment from raindrop and flow. In Eq. (1), soil eroded by raindrop is calculated with canopy ratio, rain intensity and surface water depth using the equation as follows [7].

$$\boldsymbol{D_R = (1 - C_g) k_r (KE)} \quad (1)$$

where, D_R is soil detachment by raindrop impact (g m^{-2} s^{-1}), k is an index of the detachability of the soil (g J^{-1}). KE is the total kinetic energy of the rain (J m^{-2}), z is an exponent ranging between 0.9 and 3.1, h is the depth of the surface water layer (mm), Cg is the proportion of canopy cover in each grid.

In Eq. (2, 3), soil eroded by sheet flow on the surface occurs with when hydraulic shear stress is larger than critical hydraulic shear stress using the equation as follows [8].

$$\boldsymbol{D_F = K_f \left(\frac{\tau}{\tau_c} - 1\right) \quad (\tau > \tau_c} \quad (2)$$

$$\boldsymbol{D_F = 0} \qquad (\boldsymbol{\tau < \tau_c}) \quad (3)$$

Where, D_F is overland flow detachment (kg m^{-2} s^{-1}), K_f is an overland flow detachability coefficient (kg m^{-2} s^{-1}), here 10 (mg/m^2) is used, τ_c is critical shear stress for initiation of motion, which is obtained from the Shield’s curve (N m^{-2}) and τ is hydraulic shear stress (N m^{-2}).

3.2.2 Sediment transport process

The eroded soil on each hillslope would flow into the main stream and get dissolved in suspended load. The detachment or deposition in the river is expressed using the equation as follows [9]. In Eq. (4), the process of deposition to the bed and detachment from bed is calculated by transport capacity concentration and SS concentration. If it is larger than *Cs*, entrainment occurs. If it is smaller than *Cs*, deposition occurs. However, bed load was ignored in this case.

$$DF_{river} = \beta_s w\, v_s\, (TC - C_S) \quad (4)$$

$$\beta_s = 0.79e^{-0.85J} \quad (5)$$

Where, DF_{river} is the flow detachment or deposition (m^3 s^{-1} m^{-1}), C_S is sediment concentration in each flow-interval (kg m^{-3}), *TC* is Transport capacity concentration ($m^3\,m^{-3}$), *w* is the width of the flow (m), v_s is the particle settling velocity (m s^{-1}) and β_s is a correction factor to calculate cohesive soil erosion, *J* is soil cohesion (kPa).

3.2.3 Model setup

The input data for the model include weather data, topography data, soil properties, land cover. In this study, the GTOPO30, global Digital Elevation Model (DEM) data with a horizontal grid spacing of ~20 km^2 (grid area: 2 × 2 min) resolution was used to delineate the Mekong River Basin. The land cover and soil type for the basin, obtained from global land cover 2000 (http://edc2.usgs.gov/glcc/eadoc2_0.php) and FAO soil map of the world [10] respectively. The elevation data were first aggregated to 3.6 km × 3.6 km resolution, and land cover and soil data were aggregated by reclassifying the land-use data for nine classes, and the soil data for eight classes. Daily precipitation and air temperature data from 65 station weather stations were obtained from the Mekong River Commission (MRC) in this river basin.

Annual records of discharge and suspended sediment concentration in the study are being extracted from the series of historical record published by the MRC. The publications tabulated measurements of water discharge, suspended sediment concentration (SSC), water quality and other physical characteristics of a series of gauging stations located along the Mekong River and its tributaries. In view of this study, flow and SSC records from three stations (Fig. 1) located in the mainstream were identified, of which records three stations were used to calculate the sediment load (Chiang Saen, Khong Chiam and Phnom Penh). The stations were selected based on their relative location from one another and the completeness of flow and sediment records for the station. Unlike discharge which was measured daily, measurements of SSC were relatively sporadic, sampling frequency is monthly and measurements of sediment concentration were not conducted at several gauging stations due to the political unrest in some of these areas. SSC samples were collected near the surface of the river (0.3 m depth) in the middle of the mainstream [11]. The estimation of suspended sediment load is challenging in the Mekong River, given that many gauging stations do not document relatively long-term sediment concentration measurements. Hence it is acknowledged that the frequency of sampling does not ensure that all ranges of the flow were sampled. In this study, monthly observed sediment load was computed from the monthly measured of suspended sediment concentration and the measured water discharge.

3.2.4 Model calibration and validation

The model was simulated for 10 years from 1991-2000 and three stream gauge along Mekong are used for calibration and validation. The period of simulation is selected depends on the data availability. Taking into account the availability of data, the daily discharge and sediment data for periods 1991 to 1995 were used to calibrate discharge simulation. Meanwhile, 1996-2000 data were used for validation. The six parameters required for calibration were initialized with empirical values, and then adjusted according to the observed discharge at different river sections. The residual soil moisture (wrsd) and the saturated hydraulic conductivity (ksat1) are the only hydrological parameters calibrated by semi-automatic calibration method. While, the two parameters of soil detachability by raindrop (k) and on overland flow (K_f) and soil cohesion (J) were initialized by empirical values [9], and then adjusted according to the observed sediment. Manual calibration was performed for soil detachment and transport parameters.

4. RESULTS AND DISCUSSION

4.1 Suspended sediment concentration simulation

To check the seasonal characteristics of suspended sediment in the river, the concentration was also simulated as shown in Fig. 2. Generally, a declining trend in mean monthly suspended sediment concentration (SSC) was observed along the entire length of the Mekong River since water quality measurement began in 1985 [12]. Figure 2 shows the monthly SSC simulation at stream gauging station for the period 1991 to 2000. The result reveals a decreasing trend in the SSC along the three regions from upstream to the downstream. This decrease trend was due to the decrease in the main stream water velocity, which increases the sediment deposition and the SSC become lower. The average monthly SSC was highest at the Chiang Saen station was estimated by 0.9 kg/m^3. While, the average SSC at Phnom Penh were estimated to be 0.25 kg/m^3. That was the lowest among the studied stations due to the sediment deposition behaviour in the Delta region, which decrease the SSC in the water. The model results also show the SSC was high in the rainy (July, August, September) season than the dry season at all three stations. That is due to the intensive soil erosion coincident with heavier precipitation.

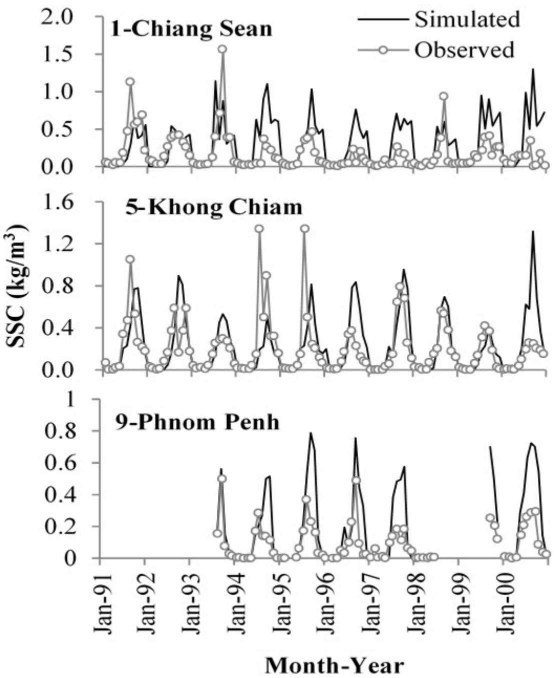

Fig. 2 Daily suspended sediment concentration (SSC) simulation at stream gauge stations for 1991-2000.

4.2 Suspended sediment load simulation

The annual sediment loads of the Mekong River were relatively stable in the past 40 years [13]. However, there is a significant seasonal change in the annual sediment loads among the year seasons. Changes in sediment loads of the Lower Mekong Basin have been analysed relying on the existing sediment data in many literatures [14], [15], [16], [17], [18]. Since the existing sediment data in the Mekong river basin have been collected by inconsistent method and had a low sampling frequency [18] studies reported different changing trends on sediment load in the Mekong River Basin. Figure 3 shows the simulated results of monthly suspended sediment load compared with measurements of upper, middle and lower monitoring stations cases from 1991-2000. The simulated results show in good agreement with observations, as reported in Table 1. The *NSE* result is greater than 0.6; 0.62, 0.62 and 0.64 for upper, middle, and lower station respectively (1991-1995) except the validation period for the Chiang Sean station (*NSE* = 0.51). A relatively highest simulation error at the Chiang Sean may have been caused by the effect of the reservoir on the upper basin of Mekong River. While, the linear correlation coefficient (*r*) between simulated and observed values was in the range of 0.80 to 0.86 for all three region stations. The model simulation was underestimated at some point but generally, the suspended sediment load was fairly well simulated at the three stations. The results also indicate that the model simulates suspended sediment load with reasonable accuracy and describing the seasonal of suspended sediment load in the Mekong River Basin, which can be applied to estimate the future suspended sediment load. The lower values of *NSE* and *r* may attribute to limitations in terms of the continuity and length of the records. As [19] also reported the lower *NSE* and *r* values for the daily sediment calibration of the Nam Ou basin in Lao PDR for a similar reason – a limited number of sediment samples for calibration. This lack also highlights the need for further investigation in the quality of the observed sediment data reflected from the sampling process and the method of sediment analysis.

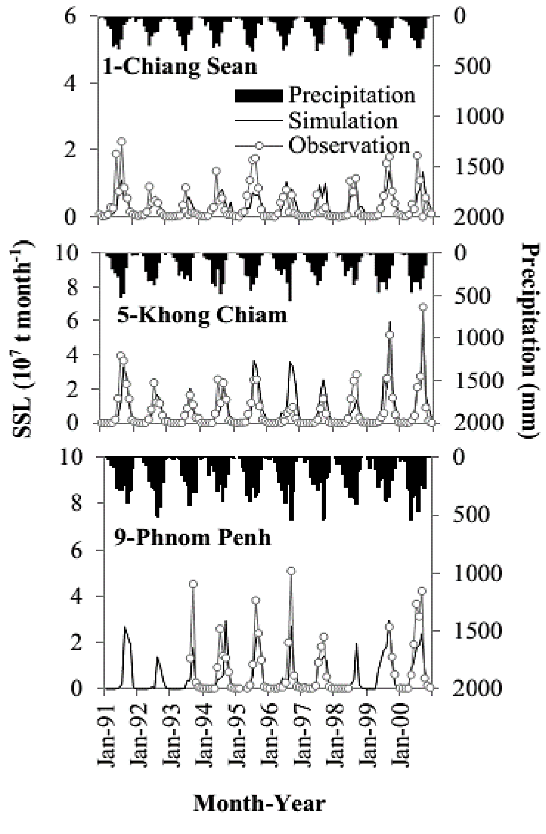

Fig. 3 Monthly suspended sediment load (SSL) simulation at stream gauge stations for 1991-2000.

In general, higher sediment load is expected during the wet season. The model results reveal that, for the entire period of 1991-2000, the average suspended sediment load a highest (76 ×

10^5 t/day) at middle region. While the upper region had a lower average suspended sediment load calculated (27 × 10^5 t/day) compared to other study region. Moreover, the monthly suspended sediment load increased with increasing basin area from Chiang Saen and Phnom Penh. The results reveal the increasing sediment load in the lower region due to deposition process. Thus, the suspended sediment load in the upper region of the Mekong River Basin was lower than the middle-lower region.

Table 2 Model performance indicators for daily river suspended sediment load simulation in Mekong River Basin from 1991 to 2000

Stations		*Performance Indicators*			
ID	*Name*	*Calibration (1991-1995)*		*Validation (1996-2000)*	
		NSE	*r*	*NSE*	*r*
1	Chiang Sean	0.62	0.85	0.51	0.65
2	Khong Chiam	0.62	0.86	0.62	0.83
3	Phnom Penh	0.64	0.80	0.64	0.87

4.3 Suspended sediment yield simulation

The resulting spatial mean distribution of annual SS yield was simulated in 1991-2000 as the model output as shown in Fig. 4. The spatial pattern of SS yield categories has five ranges of SS yield values. Three qualitative categories have been chosen for the output SS yield classes: low (SS yield range, 0.0-14.36 t km^{-2} yr^{-1}), moderate (SS yield range, 14.36-91.80 t km^{-2} yr^{-1}), and high SS yield (SS yield range, 91.80-274.52 t km^{-2} yr^{-1}). This trend can be determined by coverage of land use, indicating severely eroded area locates at the region with poor vegetation cover and topographic of the basin.

Total annual SS yield range from 0.0 to 14.36 t km^{-2} yr^{-1} are scattered in all over the MRB area. This range occupying 60% of the study area in correspondence to low steepness slope, range from 0 to 5.98% in lower region Mekong basin, in Thailand and Cambodia part, and also some part in upper region. Sand and clay of these parts, have better permeability and highly resistant to runoff impact. This total annual SS yield also is related mainly to the protective role of forest and natural vegetation cover. While, the SS yield range from 14.36 to 91.80 t km^{-2} yr^{-1} class occupying 35% in this study scattered in the middle region near Vietnam and some parts near Myanmar and Lao PDR. This is due to cropland cover and higher average annually rainfall distribution. Furthermore, type of soil is highly contents silt and sand, easy to detach due to runoff. Small parts occupying 5 % with extremely high value of SS yield, 91.80 to 274.52 t km^{-2} yr^{-1} in upper, middle and lower region especially in the valleys with steep slopes and high rainfall-runoff factor between 7986-12,599 MJ ha^{-1} mm ha^{-1}.

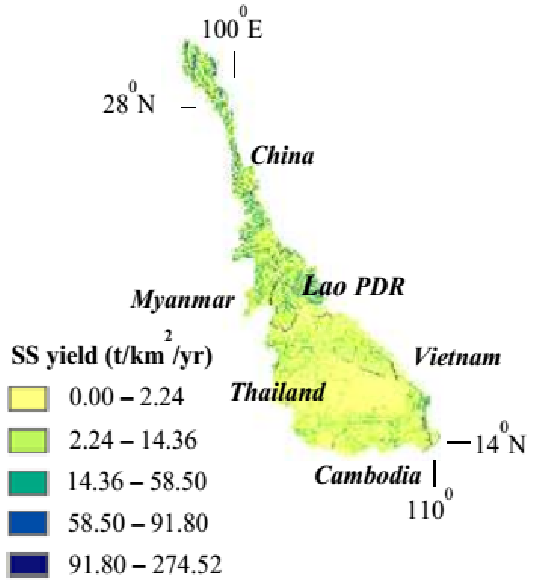

Fig. 4 Average suspended sediment (SS) yield (t km^{-2} year^{-1})

5. CONCLUSION

In this study, the sediment dynamic process was successful assessed using integrated process-based model. The main findings were as followed.

1. Integrated process-based sediment dynamic model with targeting large basin in South East Asia showed the applicability to simulate sediment dynamic process, indicating the sufficient accuracy for long term simulation.
2. The simulated suspended sediment concentration is higher in the rainy (July, August, September) season than the dry season.
3. The sediment load in the lower region Mekong River basin showed an increase due to deposition process.
4. The results provide the spatial distribution of SS yield over the Mekong River basin. SS yield 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 SS yield produced areas which deserve priority attention in basin management for soil and water conservation.

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