An Approach to the Model use for Measuring Suspended Sediment Yield in Ungauged Catchments

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ABSTRACT

Different types of water resources studies require the information of Suspended Sediment Yield (SSY) in different time resolutions. In ungauged watersheds where hydrometeorogical time series are not available, the mean annual SSY (SSY_a) is solely predictable and catchment area is traditionally used as the predictor because it is the most important variable and generally determined during project planning. Firstly, this research tried to advance the traditional SSY_a model by additionally associating global topographic data. Based on the jack-knife procedure, the modified method considering catchment area with slope greater than 15% was evaluated in 17 gauged catchments in the Lower Mekong Basin and the overall predictive accuracy was improved about 66% in term of mean absolute percentage error. Secondly, the predicted SSY_a in each modeled catchment was monthly distributed using Unit mean annual Sedimentograph (USG_a). The double-average USG_a superior to the single-average one provides overall better quality results than the regionalized USG_a dependent upon the spatial proximity approach. The model performance measured by Nash-Sutcliffe Efficiency (NSE) is about 0.66 in median value and satisfactory results (NSE >0.50) are obtained in 11 catchments. Lastly, the validated regional model was regarded as a potential and feasible tool in solving sediment-ungauged issues in the basin.

Keywords: Sediment Yield, Ungauged Catchment, Unit Sedimentograph, Spatial Proximity, Mekong Basin

1. INTRODUCTION

Sediment yield is the amount of sediment discharged by a catchment over a period of time. In alluvial rivers, it often depends on suspended load which is the predominant portion and commonly accounts for more or less 90% (Walling and Fang, 2003; Francke *et al*., 2008; Zhang *et al*., 2012). Quantification of Suspended Sediment Yield (SSY) in rivers is crucial for issues of soil erosion, water quality, reservoir sedimentation, fish habitat and other ecological impacts (Morris and Fan, 1998; Melesse *et al*., 2011; Isik, 2013). Unfortunately, sediment-observed data are lacking for rivers in many parts of the world, especially in developing and remote regions (Walling and Fang, 2003). Although some gauged rivers are existent, the sampling frequency is

commonly low (monthly or larger time scale). To deal with this problem, numerous modeling tools have been developed and empirical approach is the most popular in data-constraint areas because it does not require detailed watershed physical information. Land use, geology, hydrometeorology and other factors physically affect land surface erosion and sediment transport but it is usually difficult to collect proper and accurate data for all watersheds (Isik, 2013).

The simplest and most widely used empirical model is sediment rating curve, the average relationship between discharge and sediment (Wang *et al*., 2007; Zhang *et al*., 2012; Isik, 2013). This method can be applied to predict SSY time series with the known discharge information. On the other hand, there are also limited streamflow monitoring stations worldwide. This

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could be evidential from many recently published researches related to rainfall-runoff modeling in ungauged basins, i.e., Bao *et al*. (2012); Zhao *et al*. (2012); Cibin *et al*. (2013) and Seibert and McDonnell (2013). In this regard, another empirical approach associating catchment Area (A_0) as a predictor is often in use. Although this technique enables solely the point value prediction such as mean annual SSY (SSY_a), it is surely feasible because A_0, the most important variable, is generally determined during project planning (Tamene *et al*., 2006). Applications of the A_0-SSY_a relationship can be found in various existing studies, e.g., Verstraeten *et al*. (2002); Tamene *et al*. (2006) and Kummu *et al*. (2010).

Some developments of water resources system require the information of SSY in monthly or sometimes daily basis. Therefore, in ungauged basins, it is necessary to distribute the predicted SSY_a (from modeling tools) into smaller time scale. One possible technique is the use of Unit mean annual Sedimentograph (USG_a). In this research, ordinates of USG_a were designed as SSY_m/SSY_a where SSY_m is the mean monthly SSY and this allows backward computation of SSY_m when SSY_a is known. In gauged basins, the USG_a model can be calibrated using the observed records. To our knowledge, this is the first experimental study and therefore, related literatures are impossibly given. Methodology of the proposed USG_a model was given in next section.

A large number of hydropower projects have been planned in the Lower Mekong Basin (LMB) and majority of them is located in the basin part of Lao PDR, Cambodia and Vietnam (MRC, 2011). However, sediment data are poorly gauged or mostly ungauged at desired sites where hydropower plants are to be developed. SSY plays an important role in sustaining such developments (Isik, 2013). For instance, it is required for design of reservoir life and storage capacity (Morris and Fan, 1998). In this basin, there are in total 60 sediment monitoring stations and most of them are situated in the basin part of Thailand. Therefore, establishment of a regional model, based on gauged catchments, for use in ungauged sites is very important in this basin.

The main objective of this study is to develop a feasible regional model for predicting SSY in ungauged catchments in the LMB. First, we established an empirical approach functionable with the easily and globally available data, catchment area and topography, for SSY_a prediction. Second, we validated the proposed USG_a model in monthly distributing the predicted SSY_a. Ungauged catchment here refers to one having no hydrometeorological data such as sediment, discharge, rainfall and so forth.

2. MATERIALS AND METHODS

2.1. Study Area and Datasets

The study area is focused on the LMB covering part of Lao PDR, Thailand, Cambodia and Vietnam. It lies between latitudes 8 to 23° N and longitudes 98 and 109° E. The basin elevation varies from just over 2800 m in the highland area of Lao PDR to about zero at the coast in the delta in Vietnam (**Fig. 1**). It is influenced by two main seasons, rainy season (May-October) and dry season (November-April). The mean annual rainfall over the basin is greatly variable, ranging from less than 1000 to more than 2500 mm. This basin behaves a wide diversity of drainage patterns including simple dentritic tributary networks that resemble a branching tree, very straight rivers and a variety of irregular patterns characterized by streams with abrupt changes in course. Land use in this study area can be broadly divided into three main components: paddy, forested land and land cultivated for field crops. Paddy (about 24% of the basin area) dominates the vast low-lying alluvial plains of the basin. The large majority of the basin part of Lao PDR and Cambodia is covered by forest, a mix of evergreen and deciduous types. Field crops are extensively found within the gently sloping upland areas in Thailand. Acrisols are the most common soil type in the LMB overall and cover about 60% of the total drainage area.

Among 46 sediment gauging stations in the tributary rivers, only 18 (2 in Lao PDR and 16 in Thailand) are possibly selected for the study because others contain only few years of records with very low sampling frequency (less than one sample per month). Drainage catchment of each station was delineated using Digital Elevation Model (DEM) of 30-m resolution, downloaded from ASTER GDEM Version 2. ASTER GDEM is a product of METI and NASA. DEM was also applied for slope computation. Daily data of discharge (Q) and Suspended Sediment Concentration (SSC) were obtained from Mekong River Commission. There are no dam-reservoirs operated during which the considered datasets were observed (MRC, 2009). The SSC sampling method and data reliability discussion can be found in Wang *et al*. (2009) and Walling (2005), respectively. SSY data are derived from the product of Q and SSC. Because SSC time series contain only few samples per month, all computations in this study are monthly base. Data information and catchment characteristics are summarized in **Table 1**. It should be noted that A_5, A_{10}, A_{15}, A_{20} and A_{30} represent catchment areas with slopes greater than 5, 10, 15, 20 and 30%, respectively.

Table 1. Data information and catchment characteristics

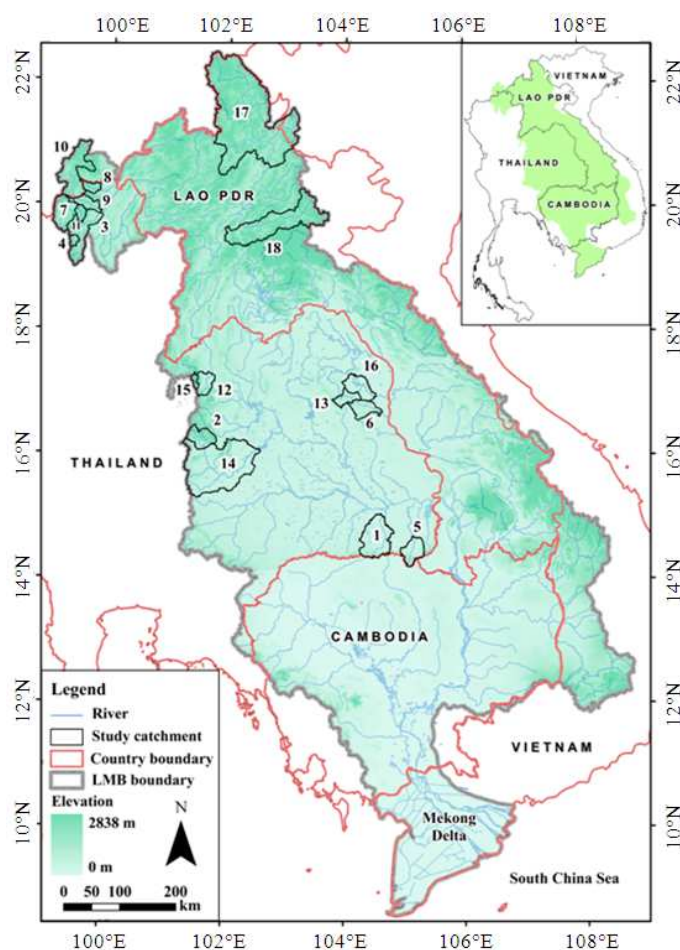| CAT	Length* (year)	A_0 (km²)	A_5 (km²)	A_{10} (km²)	A_{15} (km²)	A_{20} (km²)	A_{30} (km²)	S_c (%)	S_r (%)	Q_a (m³/s)	SSY_a (M ton/year)
1	25	3171	2296	1095	469	225	70	9	8	37.21	0.116
2	20	1405	1280	1020	770	584	350	22	15	17.10	0.062
3	20	3249	3062	2690	2308	1957	1273	27	10	23.97	0.152
4	22	260	256	244	224	198	136	32	16	2.22	0.015
5	16	1412	1203	819	505	318	136	15	16	23.81	0.060
6	14	1220	1071	789	543	376	172	17	10	18.67	0.116
7	20	1886	1738	1452	1185	975	638	26	12	25.99	0.103
8	19	522	513	488	447	393	263	32	16	11.33	0.107
9	13	6182	5903	5308	4636	3974	2654	29	26	105.00	0.760
10	34	3414	3326	3102	2782	2412	1602	31	27	68.22	0.453
11	22	428	421	403	372	333	235	34	17	5.51	0.044
12	32	1256	1128	877	648	483	266	20	15	18.38	0.135
13	34	795	696	510	331	209	83	16	14	9.09	0.055
14	27	10,806	8367	4725	2568	1582	765	12	10	57.90	0.173
15	22	233	226	207	179	150	96	29	16	10.66	0.022
16	21	2385	1919	1210	667	369	123	12	11	37.32	0.103
17	7	19,704	19,430	18,679	17,492	15,989	12,201	38	45	546.40	4.442
18	7	6482	6405	6182	5817	5344	4137	39	41	117.77	0.841

Fig. 1. Location map of the study catchments

2.2. Mean Annual Suspended Sediment Yield (SSY$_a$) Model

SSY$_a$ is traditionally predicted using empirical relationships (linear or non-linear) developed on gauged areas and the most common predictor is catchment Area (A$_0$). Topography is also an important factor involved in sediment prediction using simple empirical models (Verstraeten *et al.*, 2002). Since global DEM is currently available for free of charge, A$_5$, A$_{10}$, A$_{15}$, A$_{20}$ and A$_{30}$ were also tried alternately instead of A$_0$ itself. All relationships were checked for correlation strength and statistical significance test (t-test). The qualified relationships should have R$^2 \geq 0.49$, t$_{statistic}$ > t$_{\alpha=0.05}$ and p-value <0.01 (Heng and Suetsugi, 2013).

The jack-knife procedure was applied for evaluation purpose. The concept of this procedure is that each of the gauged catchments is in turn regarded as ungauged, termed pseudo ungauged catchment. For site-specific error measure, Percentage Error (PE) was used while Mean Absolute Percentage Error (MAPE) was employed to assess the overall predictive accuracy of each alternative SSY$_a$ model Equation (1 and 2):

$$PE = 100 \times \frac{P_i - O_i}{O_i} \qquad (1)$$

$$MAPE = 100 \times \frac{1}{n} \sum_{i=1}^{n} \frac{|P_i - O_i|}{O_i} \qquad (2)$$

where, P$_i$ and O$_i$ is respectively the predicted and observed SSY$_a$ in catchment i and n is the number of catchments. The R^2 and MAPE values of all proposed relationships were optimized. The one having optimum R^2 and MAPE was considered as the best SSY$_a$ model. Afterwards, the predicted SSY$_a$ from the best model were distributed monthly over a period of one year using USG$_a$.

2.3. Unit Mean Annual Sedimentograph (USG$_a$)

Representative mean annual sedimentograph (SSY$_m$ vs time) of each catchment was obtained by averaging SSY in each specific month. Its ordinates were then divided by SSY$_a$ (or area under the graph) to generate Unit mean annual Sedimentograph (USG$_a$). The word "unit" denotes unity of area under USG$_a$. In this research, USG$_a$ was considered as a simple linear model which can be used to monthly distribute SSY$_a$ Equation (3):

$$SSY_{m,j} = SSY_a \times U_j \qquad (3)$$

where, SSY$_{m,j}$ and U$_j$ is respectively the SSY$_m$ and ordinate of USG$_a$ for month j. In this study, we compared two alternatives of the USG$_a$ model. First is the use of average USG$_a$ in which each ordinate (SSY$_m$/SSY$_a$) was calculated as the mean of those from all gauged catchments and the jack-knife procedure was applied as well in this case. In the second alternative, USG$_a$ of the target ungauged catchment was transposed from a donor catchment using the spatial proximity regionalization approach. The hypothesis of this approach is that catchments geographically close to each other should have similar characteristics (Zhang and Chiew, 2009) and in this study corresponding to similar USG$_a$ model. Spatial proximity is advantageous for its using the full information content of the locally calibrated models. Furthermore, it favors data-constraint regions because it does not require detailed information of the catchment attributes. The Distance (D) between catchment centroids was regarded as the distance measure (Zhao *et al.*, 2012). For example, for validation in CAT-1, the donor catchment is CAT-5 which is the most nearest one (D = 70 km). Hence, the calibrated USG$_a$ in CAT-5 was selected to compute SSY$_m$ in CAT-1.

In each modeled catchment, the predicted mean annual sedimentograph was compared with the observed one so as to determine the model performance statistically measured by Nash-Sutcliffe Efficiency (NSE). For sediment modeling in monthly basis, the predictive accuracy is judged as satisfactory in case NSE is greater than 0.50 while negative NSE indicates that the observed mean value is a better predictor than the model being used Equation (4) (Moriasi *et al.*, 2007):

$$NSE = 1 - \frac{\sum_{j=1}^{12}(O_j - P_j)^2}{\sum_{j=1}^{12}(O_j - O_{avg})^2} \qquad (4)$$

where, O$_j$ and P$_j$ is respectively the observed and predicted SSY$_m$ for month j and O$_{avg}$ is the average observed SSY$_m$.

3. RESULTS AND DISCUSSION

An analysis of the available data showed that about 92% of SSY are transported during rainy season, from May to October (**Fig. 2**). The remaining 8% are transported during dry season, from November to April. In this season, the amount of SSY in November is predominant and accounts for about 4.3%. This could be explained by clockwise hysteretic effect (lag time between Q and SSY) meaning that the eroded materials in October re-deposit and they are then transported by the successive events in November (the extension of rainy season in some years).
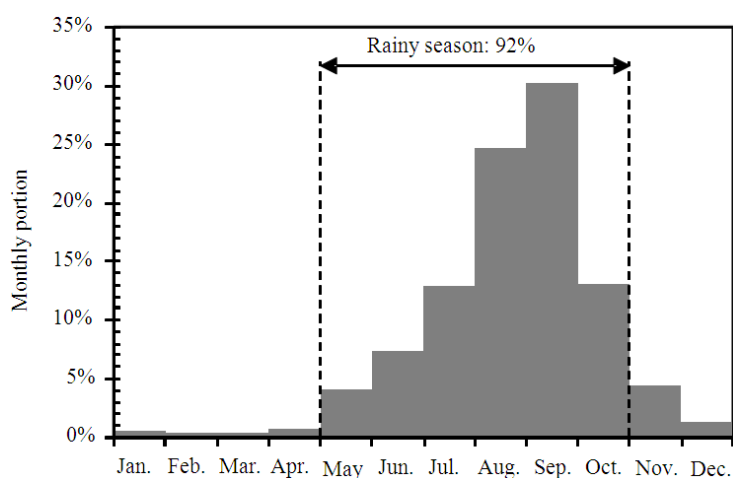
Fig. 2. Monthly distribution of SSY

More or less 83% of the peak SSY_m events occur in September while the remaining 17% do in August and October. In dry season, around 50% of the minimum SSY_m events fall in February, 33% in March and the remaining 17% in January. The temporal variation of sediment transport could be explained by climate variation and local extreme phenomena such as flood, slope failure.

3.1. Prediction of SSY_a

Excluding Catchment No. 17 (CAT-17), CAT-14 has the maximum A_0 and A_5 but its corresponding SSY_a is less than that of CAT-9, CAT-10 and CAT-18. This could be explained further by the topographic feature of each catchment. Steeper catchments generally expose to higher intensity of soil erosion. Overall, CAT-14 contains A_{10}, A_{15}, A_{20} and A_{30} values less than those of CAT-9, CAT-10 and CAT-18. Together with the evidence of low R^2 value, there is no significant relationship between SSY_a and the size of drainage Area (A_0) alone.

CAT-17 behaves not only the largest A_0 but also A_5, A_{10}, A_{15}, A_{20} and A_{30}. It contains the largest SSY_a of 4.442 M ton/year with the corresponding highest mean annual discharge (Q_a) of 546.40 m³/s. This catchment is characterized by steep river channel (river channel slope gradient (S_r) = 45%) producing high unit stream power with the potential for riverbed erosion and sediment transport. It also behaves steep drainage terrain (catchment slope gradient (S_c) = 38%) corresponding to high erosive factor with the potential for land surface erosion. By visualizing the scatter plots of A-SSY_a, CAT-17 scatters far away from others and thus not accounted for in the regression analysis to avoid high uncertainty in predicting SSY_a.

Table 2 presents the statistical characteristics of each A-SSY_a relationship. The entire relationships pass the statistical test and this reveals the use of adequate sample size for regression fitting. Only A_0 exhibits poor correlation with SSY_a (R^2 < 0.49). This clearly demonstrates that the traditional method associating A_0 as the predictor is very uncertain. As shown in **Fig. 3**, R^2 value increases continuously from A_0 to A_{15} and it is rather constant from A_{15} to A_{30}. In case of MAPE, it significantly decreases from A_0 to A_{10}. After minimizing at A_{15}, moderate increase trend is observed. In other words, the optimum value of MAPE was found with A_{15}. This result is in agreement with that of Heng and Suetsugi (2013) and could strongly justify the statement of Fuchs (2004). It should be remarked that the existing study of Heng and Suetsugi (2013) is focused on estimating quantiles of annual maximum SSY. In conclusion, A_{15} was judged as the best predictor and selected to build the empirical relationship for predicting SSY_a in ungauged catchments. The A_{15}-SSY_a relationship (R^2 = 0.9038) was determined as Equation (5):

$$SSY_a = 0.0001A_{15} - 0.0097 \qquad (5)$$

By applying the A_{15}-SSY_a linear model based on the jack-knife procedure, the predictive accuracy in each modeled catchment is tabulated in **Table 3**. In term of PE, SSY_a in ungauged catchments could be predicted with accuracy between -55% and 118% with an average absolute value (MAPE) of about 44%. Catchment heterogeneity could explain the difference in predictive accuracy spatially. Negative and positive PE value denotes the under- and over-estimate, respectively. Under-estimates are common for extreme high values. Significant large errors (PE >100%) in CAT-3 and CAT-14 are due to large variance of both catchments existent in the regression (**Fig. 4**).
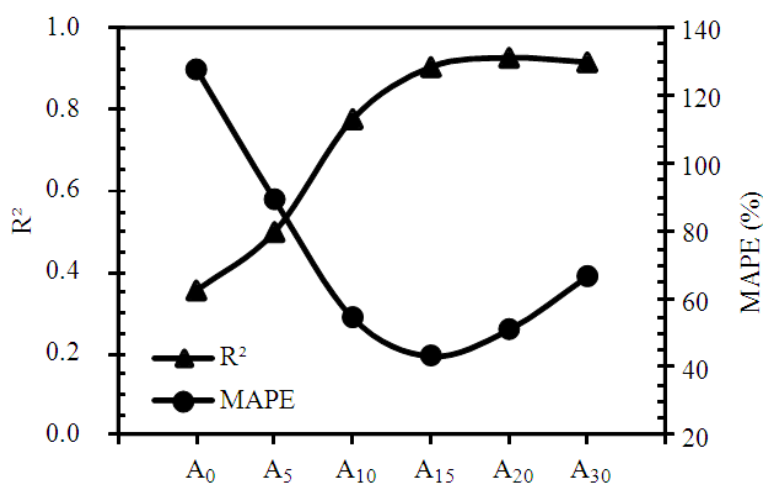
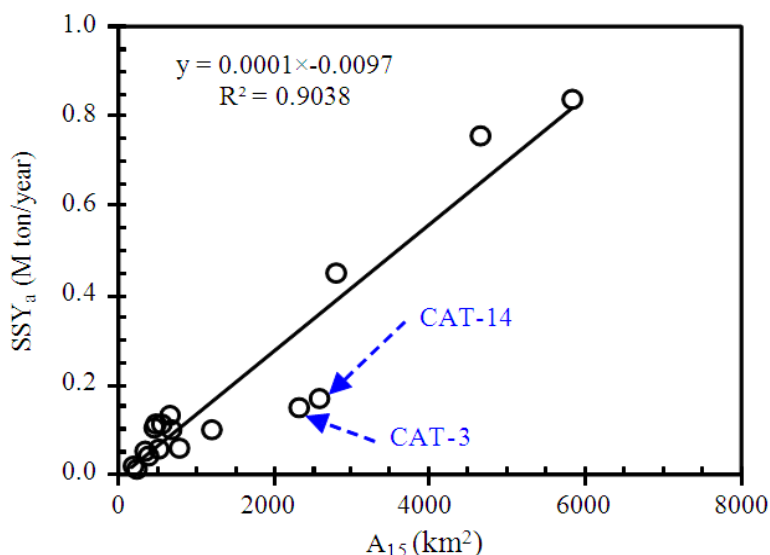**Fig. 3.** Optimization of the proposed SSY_a models

Fig. 4. Graphical illustration of the A_{15}-SSY_a relationship

Table 2. Statistical characteristics of the A-SSY_a linear relationships

Predictor	R^2	$t_{statistic}$	p-value	MAPE (%)
A_0	0.36	2.875	0.0090	128
A_5	0.50	3.864	0.0011	90
A_{10}	0.78	7.215	< 0.0001	55
A_{15}	0.90	11.873	< 0.0001	44
A_{20}	0.93	13.736	< 0.0001	51
A_{30}	0.92	12.744	< 0.0001	67

3.2. Distribution of SSY_a Using Average USG_a

It should be noted that CAT-17 was also excluded in this section. The predicted SSY_a in each modeled catchment was distributed monthly based upon the average USG_a graphically illustrated in **Fig. 5**. Using the jack-knife procedure, the predictive accuracy in term of NSE varies from -2.38 to 0.97 (median = 0.61). There are in total 10 satisfactorily modeled catchments (NSE > 0.50). Similarly, significant low accurate results occur in CAT-3 and CAT-14. This could be explained by large errors containing in the predicted SSY_a.

Using only the single model of average USG_a might not represent well diversity of catchment characteristics. In **Fig. 5**, it is evident that there is a

remarkable gap between two groups of site-specific USG_a: Under and above the peak of 0.306. It also means that the single-average USG_a is distorted because there is no any peak in the group having that value (0.306) or close proximity. In order to advance the predictive accuracy, various catchment attributes were used alternately as constraint variable to classify the site-specific USG_a and A_0 was found as the best one. In this classification, there are nine and eight USG_a located under and above A_0 of around 1650 km^2, respectively. Average USG_a was then computed for each group as depicted in **Fig. 5**. It can be seen

that the double-average USG_a represents better the entire candidate USG_a.

By employing the double-average USG_a model, the predictive accuracy in each modeled catchment is presented in **Table 3**. NSE ranges from -1.94 to 0.96 with a median value of 0.66. There are 11 satisfactorily modeled catchments in this case. In comparing with the results yielded from the single-average USG_a, the uncertainty (range of NSE) was reduced together with larger median NSE about 8%. Number of satisfactorily modeled catchments also increases. To sum up, the double-average USG_a is superior to the single-average one.
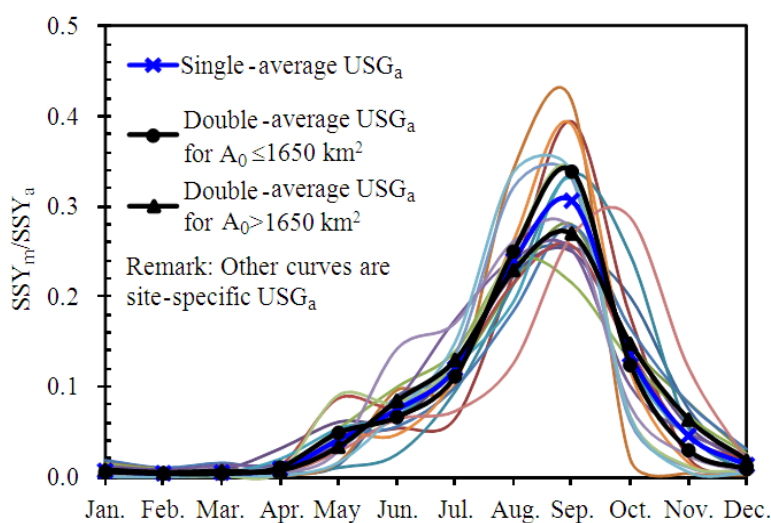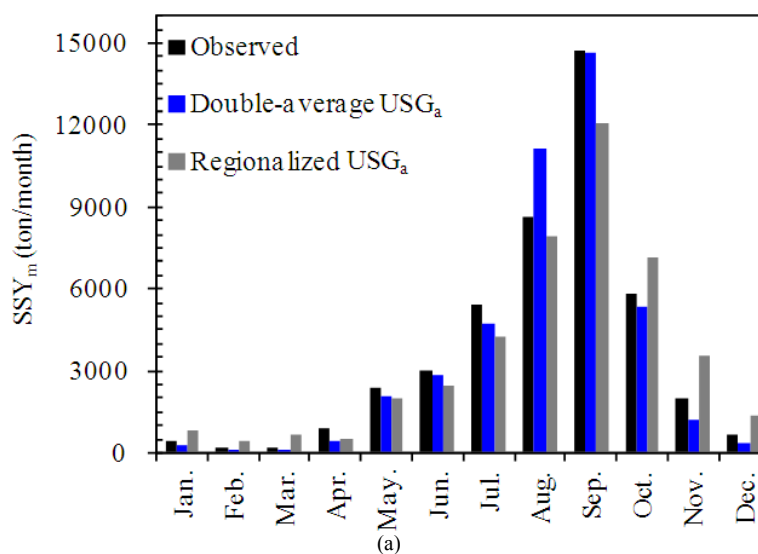

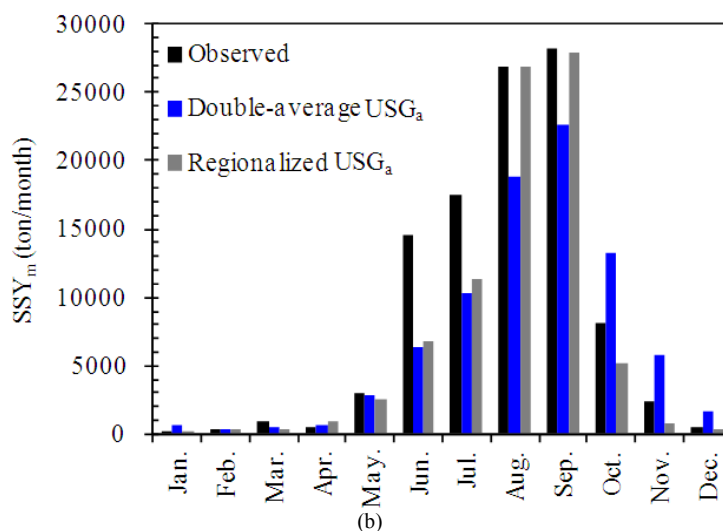**Fig. 5.** Unit mean annual sedimentograph (USG_a)

(a)

Fig. 6. Comparison between the predicted and observed SSY_m in (a) CAT-11 and (b) CAT-16

Table 3. Site-specific model performance

| CAT | PE (%) (SSY_a model) | NSE (SSY_m model) | | | Donor catchment* |
		Single-average USG_a	Double-average USG_a	Regionalized USG_a	
1	-55	0.43	0.40	0.50	5
2	66	0.55	0.47	0.19	14
3	118	-2.38	-1.82	-1.42	4
4	52	-0.01	-0.41	0.26	3
5	4	0.87	0.82	0.91	1
6	-45	0.48	0.52	0.51	16
7	58	-0.24	-0.01	-0.14	11
8	-54	0.47	0.51	0.35	9
9	-20	0.88	0.90	0.90	10
10	-16	0.90	0.90	0.88	9
11	-3	0.97	0.96	0.93	7
12	-42	0.61	0.66	0.66	15
13	-35	0.67	0.71	0.70	16
14	116	-2.37	-1.94	-3.43	2
15	-30	0.76	0.81	0.86	12
16	-19	0.84	0.79	0.91	13
17	-	-	-	-	-
18	-5	0.87	0.78	0.86	17

*Catchment whose USG_a is transposed to the target ungauged catchment (use in the regionalized USG_a alternative)

3.3. Distribution of SSY_a Using Regionalized USG_a

Exclusively for regionalization purpose, CAT-17 was taken into account because it can introduce a diversity that could be advantageous for ungauged catchment modeling (Oudin *et al.*, 2008). In this section, the predicted SSY_a in each modeled catchment was distributed monthly based upon USG_a regionalized using the spatial proximity approach. As a result shown in **Table 3**, the predictive accuracy measured by NSE ranges between -3.43 and 0.93 (median = 0.66). There are also 11 modeled catchments having NSE value greater than 0.50. In comparing with the double-average USG_a, the uncertainty was increased although the median NSE value of both approaches is approximately the same.

Moreover, the regionalized USG_a technique performs worse (less NSE) in 10 out of 17 catchments. In these 10 catchments (No. 2 and 6-14), the prediction was deteriorated overall for peak value (in September). It is vice versa in other seven catchments. **Figure 6** shows an example of time series comparison in CAT-11 and CAT-16. Shortly, the regionalized USG_a is inferior to the double-average USG_a.

4. CONCLUSION

In the LMB, huge amount of hydropower, irrigation and other water-related projects requiring the information of sediment for the design and management have been planned in the basin part of Lao PDR, Cambodia and Vietnam where sediment data are poorly gauged or ungauged. Therefore, this study is to develop a regional SSY model for use in ungauged areas. Firstly, accuracy of the traditional method for SSY_a prediction was advanced by substituting A_0 (the predictor) with A_{15} and the overall predictive accuracy in term of MAPE was improved about 66%. Then the predicted SSY_a in each modeled catchment was distributed monthly by mean of USG_a. The double-average USG_a superior to the single-average one offers overall better quality results than the regionalized USG_a dependent upon the spatial proximity approach. The inferiority of the regionalized USG_a could be attributed to the sparse network of catchments used in the study.

As a whole from statistically comparing the model results with the corresponding observed data in each study catchment, SSY_a and SSY_m in ungauged areas could be measured with an accuracy of 44% in term of MAPE and 0.66 in term of median NSE, respectively. Last but not least, the proposed approach could be potentially and feasibly employed to provide solutions to sediment-ungauged issues in the basin. This research is also an important work to be referred in land management and planning.

5. ACKNOWLEDGEMENT

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