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ESTIMATING THE SAMPLING FREQUENCY AND ACCURACY OF SUSPENDED SEDIMENT FLUX OF THE RED RIVER SYSTEM (VIETNAM)

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ABSTRACT

Based on dataset of daily water discharges and suspended sediment concentrations of the Red River during 2005-2011 period, we have analyzed the influence of sampling frequency on uncertainty of suspended sediment flux estimates and pointed out the need of adapted sampling frequency strategies. Seven kinds of sampling frequency from monthly to one sample every two days were tested for the Red River at LaoCai, PhuTho and SonTay stations and the Da and Lo Rivers. The results obtained showed that the range minimum-maximum flux estimates decrease significantly with increasing sampling frequencies and error values of simulation tended to approach 0%. If a deviation of simulated flux estimates lower than ±15% from the reference fluxes is accepted, the Red River at LaoCai and PhuTho sites must be sampled at least 8 samples per month (i.e. twice-weekly) and the Red River at SonTay, the Da and Lo Rivers must be sampled at least 4 samples per month (i.e. weekly).

Keywords: Red River, suspended sediment flux, sampling frequency, empirical model, error.

1. INTRODUCTION

The fluvial transfer of sediment from the land to the coastal areas and/or the ocean reflects the denudation of the continents and contributes to new depositional environment [1 - 4]. Furthermore, quantifying accurate the sediment flux delivery to the ocean is fundamental to (i) establish global biogeochemical cycles (e.g. for the carbon or nutriment cycles, [5, 6]), (ii) understand many physical processes (e.g. evolution of landscape and coastal landforms, [7, 8]), and (iii) evaluate its potential role as a pathway for pollutants from terrestrial to coastal and marine systems [9, 10]. However, important uncertainties persist, mainly due to the non-stationary nature of the sediment fluxes and the use of dated and/or questionable data (short-term sampling, inappropriate sampling frequency and/or data collected before dam-reservoir construction, deforestation or climatic change [11, 12]).

There are various studies on sediment load by river using a wide range of different sampling frequencies, including monthly sampling (e.g. [13]), weekly sampling (e.g. [14]) and daily sampling (e.g. [15]). However, in many rivers a great part of annual load is carried in only 5 or 10 days [16] and, thus, correct estimation of sediment flux is difficult. Although many studies outline the problem of the accuracy of annual suspended sediment flux estimates, only few studies have addressed the quantification of errors-related to inadequate sampling strategy (e.g. [17,18]).

The Red River (China/Vietnam), one of largest rivers draining the Himalaya Mountains into South-East Asia, plays an important role in the economic, cultural and political life of the Vietnamese people. Based on the dataset obtained from high frequency measurements of suspended sediment concentrations and water discharge (daily) collected between 2005 and 2011 at the five permanent observation stations along the Red River system, the aim of this paper is to analyze the influence of sampling frequency on the uncertainty on suspended sediment flux estimates. We simulated suspended sediment flux estimates that would be obtained by using lower sampling frequencies. Maximum errors are quantified for different sampling frequencies in order to determine the minimum frequency giving realistic annual load estimates for the five key sites.

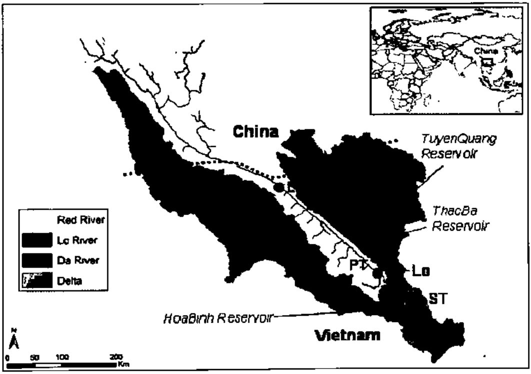

Figure 1. Description of the Red River watershed and location of study sites.

2. MATERIALS AND METHODS

2.1. Area descriptions

The Red River system (Figure 1), located in South-East Asia, has a total watershed area of 169 000 km^2, 50.3 % of which in Vietnam, 48.8 % in situated in China and 0.9 % is situated in Laos and includes a fertile and densely populated delta plain. The Red River originates from the mountainous area of Yunnan Province in China, flows 1200 km south-eastward and then flows through seven Vietnamese provinces before flowing into the Gulf of Tonkin in the South China Sea.

The main tributaries of the Red River are the Da River, on the right bank, and the Lo River, on the left bank (Figure 1). The Da River has its source in the Yunnan Province, near to that of the upstream Red River, at an elevation of more than 2000 m. The Lo River also comes from China at an elevation of about 1100 m.

The Red River basin is characterized by two distinct seasons: the wet season from May to October and the dry season from November to April (Figure 2). The mean annual water discharges for the 2005-2011 period were 542 m^3/s, 678 m^3/s and 3171 m^3/s for the Red River at LC, PT and ST sites. For the same period, the mean annual water discharges of the Da and Lo Rivers were 1717 m^3/s and 809 m^3/s, respectively.

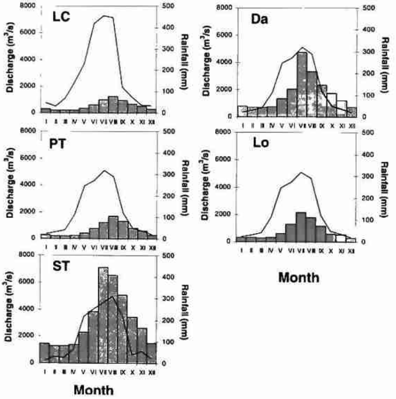

Figure 2. Description of monthly averages of water discharge (m^3/s) and rainfall (mm) of the Red River at five strategic permanent observation sites from 2005 to 2011 (data from IMHE).

2.2. Data and methodology

Daily monitoring of water discharge and suspended sediment concentrations was performed by the Vietnamese Institute of Metrology, Hydrology and Environment (IMHE) at five strategic permanent observation sites from 2005 to 2011 (Figure 1):

(1) the LaoCai gauging site (simplified by LC) corresponds to the entry of the Red River in Vietnam and represents river borne material derived from the Upper Red River draining from China;

(2) the PhuTho gauging site (simplified by PT) is situated at the outlet of the Red River before the confluence with the Da and the Lo Rivers;

(3) the HoaBinh gauging site (simplified by Da) is located at the outlet of the Da River and integrates material derived from the Da system after the HoaBinh Reservoir;

(4) the VuQuang gauging site (simplified by Lo) is located at the outlet of the Lo River;

(5) the Sontay gauging site (simplified by ST), near Hanoi, is located at the downstream of the confluence with the three main tributaries (Red, Da and Lo Rivers) and at the upstream limit of the dynamic tide; this site is considered to be the outlet of the Red River system and the entry point to the Red River Delta.

Annual reference suspended sediment flux

Based on well known methods [2, 5, 7, 17], and daily water discharge and suspended sediment concentrations, the suspended sediment fluxes have been calculated for each year at each site as follows:

$$F_{Ref} = \sum_{i=1}^{n} \mathbf{Fi} \quad \text{with } \mathrm{Fi} = Ci\ Qi$$

where: F_{Ref} is the reference annual suspended sediment flux; Fi is the instantaneous suspended sediment flux; and Ci and Qi are the instantaneous suspended sediment concentrations and water discharges (daily) and n = 365 or 366.

Simulation of various temporal sampling frequencies

The suspended sediment fluxes estimated from the whole database, i.e. representing the most accurate estimates available from our data, are considered as reference fluxes (F_{Ref}). In order to test the effect of sampling frequency on suspended sediment flux estimates, different fixed period strategies corresponding to lower sampling frequencies are simulated by extracting individual sediment concentrations and corresponding discharge values from the database (reduced datasets). For each simulation using reduced datasets, minimum and maximum annual suspended sediment fluxes are retained. Then, these extreme suspended sediment fluxes are compared to the corresponding F_{Ref} to quantify the range of estimate errors that would be done when using low sampling frequencies. The different simulations correspond to different models reflecting various sampling strategies (monthly, bi-monthly, weekly, twice-weekly, every 3 days, and every 2 days).

We have tested two kinds of simulations for monthly sampling (M1 and M1*). We have simulated irregular monthly sampling (M1*) by randomly selecting one sediment concentration for each month. Each of the 12 randomly selected suspended sediment concentrations (considered as representative of the month) is multiplied by the corresponding monthly mean water discharge. The sum of these 12 monthly sediment fluxes gives an annual suspended sediment flux. The simulation has been repeated one million times to obtain a statistically representative information.

The minimum and maximum suspended sediment fluxes obtained by these simulations are kept and compared to the reference flux. The modified version (simulation M1) represents a regular sampling frequency of one sample per month with fix 30 days intervals. The first suspended sediment concentration is randomly selected in the first month of the year. For the rest of the year, suspended sediment concentrations are selected at 30 days intervals. Each of the randomly selected suspended sediment concentrations (considered as representative of a period including 15 days before and 14 days after the sampling day) is multiplied by the corresponding 30 days mean water discharges. The sum of these suspended sediment fluxes gives the annual suspended sediment flux estimates (29 possibilities).

Model M2 simulates a frequency of two samples per month (one sampling day in the first half of the month and another in the second half). The suspended sediment concentrations are randomly selected in the half of the month, considered as representative for the respective period of time and multiplied by the corresponding mean water discharge. Again, one million simulations have been performed.

Model M3 represents weekly sampling. The first suspended sediment concentration is randomly selected in the first week of the year. For the other 51 weeks of the year, suspended sediment concentrations are chosen at 7 days intervals to simulate a sampling realized always the same day of the week (for example every Monday). Each selected value of suspended sediment concentration is multiplied by the corresponding average weekly discharge. Model M4 simulates a sampling frequency of two samples per week. For each week, we choose two suspended sediment concentrations with a minimum space of 24 h between the two samples. All 12 possible combinations were tested. Model M5 (one sample every 3 days); Model M6 (one sample every 2 days). For each possible combination, the selected suspended sediment concentrations were multiplied by the average of discharges calculated over the corresponding sampling period.

3. RESULTS AND DISCUSSION

3.1. Suspended sediment fluxes loaded by the Red River system with different sampling frequencies

For the three sites along the main channel of Red River and the two major tributaries Da and Lo Rivers, seven different sampling strategies have been simulated by estimating suspended sediment fluxes from randomly extracted individual suspended sediment concentrations and corresponding discharge values from the whole database. The annual sediment flux estimates from different kinds of simulation and reference annual flux for each station during 2005-2011 are presented in Table 1.

During the whole observation period, the resulting range between minimum and maximum flux estimates decrease significantly with increasing sampling frequencies for all five permanent stations (Tables 1). For example, when simulation M1* (irregular sampling intervals; one sample per month) is applied to data obtained for the Red River at LaoCai in 2005, simulated annual suspended sediment flux estimates range from 19.6 Mt/yr to 100 Mt/yr; and its values ranged between 59.5 Mt/yr and 59.7 Mt/yr for the simulation M6 (one sample every 2 days); whereas the reference flux was 59.7 Mt/yr (Table 1). We noted that if the extreme value was observed in the Red River at PhuTho in 2005 when simulation M1* is applied with the suspended sediment flux estimate varied up to 225 Mt/yr (the reference flux of 56.7 Mt/yr, Table 1), while the lowest value of flux estimate (0.7 Mt/yr) was observed with model M1* for the Lo

River in 2005 (reference flux of 8.0 Mt/yr, Table 1). This result showed clearly that monthly sampling was not appropriate to get reliable annual suspended sediment flux estimates for the Red River system.

Table 1. Results of simulations for the Red River at LaoCai, PhuTho, SonTay sites and for the Da and Lo Rivers.

Year/Flux	M1* ($x10^6$t/yr)	M1 ($x10^6$t/yr)	M2 ($x10^6$t/yr)	M3 ($x10^6$t/yr)	M4 ($x10^6$t/yr)	M5 ($x10^6$t/yr)	M6 ($x10^6$t/yr)	Fref ($x10^6$t/yr)
Red River at LaoCai								
2005	19.6-100	25.6-89 4	34.1-77 9	53.1-64.1	58.7-59.4	54.3-66.5	59.5-59.7	59.7
2006	29.3-101	35.3-150	53.2-121	76.6-114	82.6-101	85.6-107	95.3-102	99.0
2007	20.5-100	24.5-71.7	34.3-66.8	44.8-56.9	44.1-56.3	48.0-55.8	50.5-53.0	52.1
2008	6.1-81	13.3-50 4	15.4-45 5	22.1-32.7	22.7-32.8	26.1-33.3	28.5-30.5	29.6
2009	10.5-82.2	15.8-51 1	22.2-36.5	26.1-38.6	31.6-37.4	33.7-34.1	32.9-35.9	34.3
2010	6.2-52.3	10.2-30.7	15.7-24 8	15.9-30.6	18.2-24.9	20.7-24.0	22.1-23.3	22.7
2011	5.9-50.2	7.7-30.5	13.1-29.6	17.3-23.1	20.6-22.5	21.0-22.9	22.1-22.1	22.2
Red River at PhuTho								
2005	19.9-225	25.1-170	40.1-108	45.5-83.2	48.4-64.7	49.1-63.6	51.5-60.4	56.7
2006	27.7-122	37.9-85.8	44.8-73.5	51.7-70.5	54.5-62.9	56.4-59.0	56.1-60 8	58.0
2007	8.8-64.9	14.9-44.9	18.9-37.3	20.8-35.4	24.1-27.8	23.6-29.5	24.8-26 9	25.8
2008	15.4-63.6	23.2-43.3	26.9-40.7	28.0-38.7	30.1-36.2	32.1-34.3	33.1-33.3	33.2
2009	11.4-51.5	13.9-36.5	18.5-31.0	20.9-29.0	22.4-27.7	24.6-26.8	25.4-25.5	25.6
2010	8.6-52.4	11.1-36 0	15.1-28.7	18.2-29.9	22.1-24.3	22.3-25 3	22 9-23.8	23.6
2011	13.9-77.0	19.4-50.2	28.4-42.7	29.5-42.0	33.8-36.4	33.7-35 6	34 1-35.7	34.8
Red River at SonTay								
2005	25.6-101	32.8-77.6	38.5-68.9	48.9-56 6	51.1-56 6	53.6-53.9	53.3-54.0	53.9
2006	40.4-185	52.5-155	61.4-112	68.8-96.6	74.0-89 2	76 7-84.4	77.1-85.7	82.2
2007	31.9-80.5	39.0-72.0	45.2-66.3	54.3-58.4	52.5-62.6	52 9-57.7	53.2-58.9	56.1
2008	23.3-67.3	28 9-51.0	35.8-46.6	36.0-48.1	38.4-41.8	39.5-41.5	39.9-41.6	40.9
2009	23.4-73 2	31 1-55.6	33.7-47.1	37 7-47.9	40.3-42.0	39 1-42.5	40.9-41.9	41.6
2010	11 6-47.7	17 0-30.9	18.3-31.7	21.0-26.1	22.8-25.2	21.6-27.7	23.8-24.4	24.4
2011	7.5-33 2	9.7-22.2	14.4-21.2	16.6-19.7	18 0-18.8	18.2-18.9	18.4-18 6	18.6
Da River								
2005	2.6-10.1	3.9-8.1	4.6-7.3	5.6-6.4	5.8-6.1	5.7-6.1	5.9-6.0	5.9
2006	4.3-11.9	5.9-10.1	6.6-8.8	7.3-8.2	7.5-8.2	7.6-7.9	7.8-7.9	7.8
2007	6.1-15.4	8.1-14.5	8.7-13.0	10.0-12 1	10.2-11.5	11.0-11.5	11.2-11.4	11.3
2008	3.5-8.4	4.0-7.7	4 6-6.9	5.3-5.8	5.3-5.8	5.4-5.5	5 4-5.6	5.5
2009	3.3-7.5	4.4-6.0	4.8-5.8	5.2-5.5	5.2-5.5	5.2-5.4	5.3-5.4	5.3
2010	1.5-4.3	2.1-3.3	2.2-3.2	2.4-2.9	2.5-2.8	2.5-2.7	2.5-2.7	2 6
2011	0.6-5.8	1.2-4.7	1.7-3.5	2.5-2.9	2.5-2.9	2.6-2.9	2.6-2.8	2 7
Lo River								
2005	0.7-18.4	3.4-13.8	6.4-9.6	7.3-8.7	7.5-8.5	7 8-8.2	7.8-8.5	8 0
2006	2.1-20.2	7.0-14 5	8.5-12.7	10.1-11.5	10.4-11.0	10.3-10.8	10.6-10.7	10.6
2007	2.1-8.6	4.1-7.0	4.6-6.1	5.0-5.7	5.2-5.6	5.3-5.5	5.4-5.5	5 4
2008	1.7-4 9	2.5-4.5	2.8-4.0	3.1-3.8	3 5-3.6	3.5-3.5	3.5-3.6	3.5
2009	2.0-5.7	2.7-5.2	3.1-4.5	3.6-3.9	3.6-3.9	3.7-3.8	3.7-3.8	3.7
2010	4.5-12.5	7 2-9.8	7.8-9.5	8.4-8.9	8.4-8.9	8.4-8.8	8.5-8.8	8.6
2011	3.1-8.8	4.2-6.7	4.5-6 3	4.8-5.7	5.0-5 7	5.1-5.5	5.4-5.4	5.3

3.2. Sampling frequency and accuracy of SPM flux estimates

Annual suspended sediment fluxes obtained from the different models were compared to reference fluxes in order to estimate the error range for a given sampling frequency. In order to compare the results obtained for the Red River and two major tributaries (Da and Lo Rivers) during 7 years (2005-2011) covering different hydrological conditions, we calculated relative errors (E_R) as follows:

$$E_R = (F_{SIM} - F_{REF})/F_{REF} \times 100\ \%$$

where F_{SIM} is the simulated annual flux estimate and F_{REF} is the reference annual flux. The results obtained were presented in Figure 3.

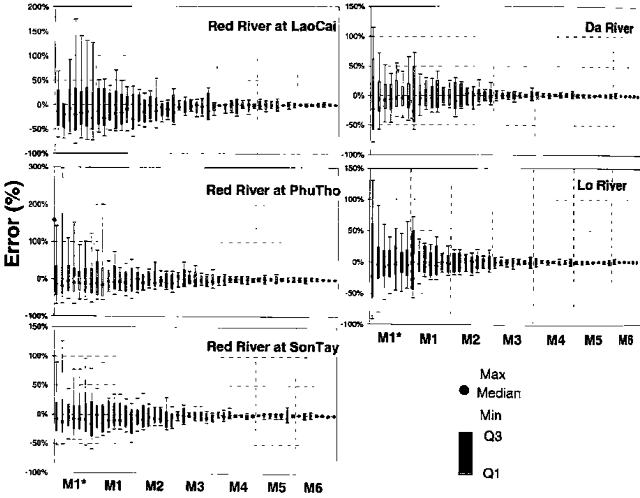

Figure 3. Results of simulated suspended sediment flux for the Red River system at five stations. The 0% level presents reference suspended sediment fluxes calculated from the complete database. In each sampling model (M1*, M1-M6) the years 2005-2011 are presented from left to right. Q1 and Q3 represent precision (10-percentile and 90-percentile) of results obtained by different frequency simulations.

We observed, for example, E_R values for annual suspended sediment flux estimates from irregular monthly sampling (M1*) range from -65 % to 297 % for the Red River at PhuTho site in 2005 (Figure 3) and range from -91 % to 130 % for the Lo River in 2005. This simulation suggests that irregular monthly sampling may produce annual sediment flux estimates with error between underestimation of 65% and overestimation up to 297 % for the Red River at PhuTho and between underestimation of 91% and overestimation of 130 % for the Lo River. In addition,

Figure 3 showed that the median values of the E_R distributions of suspended sediment flux estimates for most simulated cases of low sampling frequencies (e.g. M1*, M1 or M2) lead systematically to underestimation of suspended sediment fluxes (Figure 3). The range of possible E_R values produced by the tested simulations is largest for the lowest sampling frequency (M1*), and E_R ranges narrow with growing sampling frequency (Figure 3). With increasing sampling frequency from M1 (i.e. regular sampling frequency of one sample per month) to M6 (i.e. one sample every 2 days), for all five stations and for all years, E_R values tended to approach 0 % (i.e. flux estimates are close to reference fluxes, Figure 3).

Considering that reliable annual suspended sediment flux estimates should always be within ±15 % deviation from the reference flux, the results allow defining minimum sampling frequencies for the five stations measured. By plotting E_R values vs. sampling frequency (number of samples per month), we compared the simulations for the different years and sites (Figure 4). The Figure 4 showed clearly that for the Red River at SonTay and the Da and Lo Rivers, suspended sediment flux estimates obtained from a sampling frequency with a minimum of 4 samples per month (i.e. weekly) are always within the acceptable limits (Fig. 4). However, 8 samples per month (i.e. two samples per week – twice weekly) give reliable flux estimates for the upstream Red River at LaoCai and PhuTho sites (Figure 4). For all sampling frequencies lower than weekly for the Da, Lo Rivers and the Red River at PhuTho and twice-weekly for the Red River at LaoCai and PhuTho, probabilities to obtain reliable flux estimates are not acceptable.

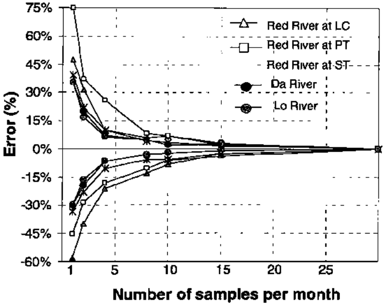

Figure 4. Comparison of maximum error percentages for simulated suspended sediment flux estimates for five stations in the Red River system as a function of sampling frequency (number of samples per month).

The higher sampling frequency of the Red River at LaoCai and PhuTho stations than at SonTay station demonstrated that the hydrodynamic of the Red River in upstream part stronger than in downstream part. This phenomenon is common in World Rivers and was explained by a decrease of surface slope from upstream to downstream of river basin [19, 20]. However, we noted that hydrodynamic of the Red River system is clearly lower than other small mountainous watersheds which require very high sampling frequency, due to important sediment transport often occurring in short intense floods (up to 100 samples per month, i.e. one sample every 7h like the Nivelle River in France, [11]). This kind of sampling frequency may be only obtained using automatic sampling systems and rarely realized [16].

4. CONCLUDING REMARKS

Based on database of daily frequency sampling of water discharge and suspended sediment concentration, we have highlighted the important of sampling frequency for reliability of suspended sediment flux estimates but also for other river parameters like salt nutriments, organic/inorganic pollutants or heavy metals transported in the particulate phase. The results obtained showed that if a deviation of simulated flux estimates lower than ±15% from the reference fluxes is accepted, the upstream part of the Red River (i.e. at LaoCai and PhuTho sites) must be sampled at least 8 samples per month (i.e. twice-weekly). Whereas, the Red River at SonTay and the Da and Lo Rivers must be sampled at least 4 samples per month (i.e. weekly). Below these minimum sampling frequencies, annual sediment flux estimates may greatly differ from reference fluxes (up to 297%) and there is high probability of systematic underestimation. These findings underline the need of adapted sampling frequency strategies for surface water quality monitoring and sediment load controlling, especially when the particulate load in river is strongly affected by anthropogenic impacts (e.g. dam/reservoir, industry, mining…).

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TÓM TẮT

XÁC ĐỊNH TẦN SUẤT LẤY MẪU VÀ ĐỘ CHÍNH XÁC TẢI LƯỢNG CÁT BÙN LƠ LỬNG CHUYỂN TẢI BỞI HỆ THỐNG SÔNG HỒNG (TRUNG QUỐC/VIỆT NAM)

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Dựa trên số liệu hàng ngày về lưu lượng nước và hàm lượng cát bùn lơ lửng của sông Hồng trong giai đoạn 2005-2011, chúng tôi đã phân tích ảnh hưởng của tần suất lấy mẫu đến quá trình ước tính tải lượng cát bùn lơ lửng chuyển tải bởi sông và chỉ ra sự cần thiết của chiến lược lấy mẫu với tần suất phù hợp. Bảy kiểu tần suất lấy mẫu khác nhau từ một mẫu/tháng đến một mẫu/hai ngày đã được thử nghiệm cho sông Hồng tại Lào Cai, Phú Thọ và Sơn Tây cũng như trên 2 sông nhánh Đà và Lô. Các kết quả thu được đã chỉ ra rằng biên độ dao động của tải lượng ước tính (giữa giá trị lớn nhất và nhỏ nhất) giảm đáng kể khi tăng tần suất lấy mẫu và giá trị sai số của tải lượng mô phỏng so với tải lượng đối chứng có xu hướng tiến dần về 0 %. Nếu độ lệch của tải lượng mô phỏng ước tính nằm trong khoảng ± 15 % so với tải lượng đối chứng có thể coi như chấp nhận được thì sông Hồng tại Lào Cai và Phú Thọ phải lấy mẫu ít nhất 8 mẫu/tháng (tức là hai lần một tuần) và sông Hồng tại Sơn Tây, các sông Đà và Lô phải được lấy mẫu ít nhất 4 mẫu/tháng (tức hàng tuần).

Từ khóa: Sông Hồng, tải lượng cát bùn lơ lửng, tần suất lấy mẫu, mô phỏng, sai số.