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Potential use of satellite observations to detect suspended sediment in delta region: a case study of the Red river delta, Vietnam

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Abstract:

Building an integrated river delta basin and coastal management plan in the context of climate change requires suspended sediments data, which plays an important role and is the key component for understanding the hydrology regime in the delta region. Sediments are responsible for carrying a considerable amount of nutrients and contaminants. Most sediment discharge data is acquired by surveys/data collection activities or by mathematical modelling. However, these methods are costly, time-consuming, and complex. Therefore, in this study, the authors investigate the potential use of satellite observations (MODIS reflectance) to detect suspended sediment flux in the Red river delta (RRD) of Vietnam. The relationships between discharge (Q), suspended sediment concentration (SSC), and total load (L) collected from the three in-situ stations Son Tay station (ST), Thuong Cat station (TC), and Hanoi station (HN) in the RRD are determined by regression analyses of reflectance data (R) obtained from MODIS bands 1-2 (250-m resolution). The results present a close connection between the monthly average of SSC and R and a good statistical relationship between the monthly average of Q and R in HN. At TC and ST, a lower correlation was found compared to HN because of the cloud cover and the position where data was collection in the river. The coefficient of determination ranged from 0.11 to 0.40 for the R-SSC and R-Q relationships. A method of estimating SSC and L at a single point along the river using data from Q and R was proposed based on the relationship correlation results.

Keywords: **delta region, discharge, MODIS, regression analysis, suspended sediment.**

Classification numbers: **2.1, 5.1**

Introduction

Suspended sediment, which includes organic and inorganic materials within the water flow, is a natural part of a river system. The primary sources of suspended sediment come from the erosion of soil, mass movements such as landslides, and riverbank erosion or human interventions on the landscape [1-3]. High amounts of suspended sediment in water can reduce the transmission of light, which not only affects the phytoplankton species in short term but also the entire ecosystem in the long term. Suspended sediment plays an important role in shaping the landscape, transporting nutrients to various species, and creating ecological habitats [4, 5]. Similarly, pollutants can adhere to suspended sediment while in transport and thus suspended sediment can influence pollutant movement. Suspended sediment is also an indicator of issues occurring in the river delta and coastal areas, which include water quality, ecological degradation, and soil and/or riverbank erosion. To develop a suitable river basin management strategy, frequent monitoring of suspended sediment is critical.

Despite the importance of suspended sediment, it is poorly gauged due to the lack of in-situ networks in many areas and especially in developing countries. We choose the RRD for this research because this region has several meteorological stations. However, they have not been operated for some time due to lack of budget and thus this region is considered to be ungauged basin. Moreover, the RRD is one of two largest and most important deltas in Vietnam; however, it has not received as much attention as the Mekong river delta. Thus, research in this area is central to the critical understanding of this important region.

Data quality is also a concern since monitoring suspended sediment depends on the number of stations, their locations, and the frequency of measurements [6]. There are some

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methods to obtain suspended sediment information such as using empirical models, physically-based mathematical models, and field sampling. Recently, the use of satellite images to detect suspended sediment has captured the attention of researchers [7-9]. There are studies that use Moderate Resolution Imaging Spectroradiometer (MODIS) images or Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery to characterize the spatial and temporal pattern of surface sediments [10-13] based on the very close relationship between R and suspended sediment concentration. Recent results show that satellite remote sensing technology is applicable and useful to obtain not only suspended sediment information but also other hydrological parameters of these ungauged areas [14].

This study aims to investigate the potential use of satellite observations (MODIS reflectance) to detect the seasonal change of suspended sediment flux in the RRD region. We first extract the satellite reflectance value at the location of the station and then apply simple regression analysis to the reflectance, discharge, suspended sediment, and total sediment load on the same day. The simple regression analysis used in this paper refers to the use of single variable (R) for one dependent variable (suspended sediment or discharge). We choose the simple regression analysis because of limitations in the available data and the objective of our research. Regression analysis performance is examined by the coefficient of determination. Only one band of reflection data was used to access the relationship with other hydrological factors. In future research, multi-band reflection data will be used to provide better results by using multi-regression analysis.

Materials and methods

Study area

The RRD is one of the largest deltas in Vietnam, the fourth largest delta in Southeast Asia in terms of delta plain size, and is also one of the chief deltas in Asia. The RRD lies in the northern part of Vietnam with a total delta area of 15000 km^2. The delta includes two large river systems: the Red river and Thai Binh river systems. The discharge in Red river is 120 km^3 of water annually and 130×10^6 ton/year of mean annual suspended sediment load. During the wet season from June to January, about 90% of the annual sediment supply is transported from a large number of distributaries. About 11.7% of the total amount of sediment goes through the Van Uc and Thai Binh river mouths, 37.8% passes through the Ba Lat mouth [15], 23.7% through the Day river mouth, and the remaining amount of sediment passes through the Tra Ly river mouth.

The climate in RRD is sub-tropical and formed by a summer monsoon from the South and a winter monsoon from the North-East. The two wet seasons account for 85-95% of the total rainfall per year [16]. The mean annual rainfall was 1590 mm and mean annual potential evapotranspiration ranged from 880 to 1150 mm per year [17].

To explore the relationship between Q-SSC, R-Q, R-SSC, and L-Q, three locations in this delta were taken into account, namely, ST, TC, and HN. ST is located upstream of the Red river and TC and HN are located at the Duong river and Red river, respectively, as shown in Fig. 1.

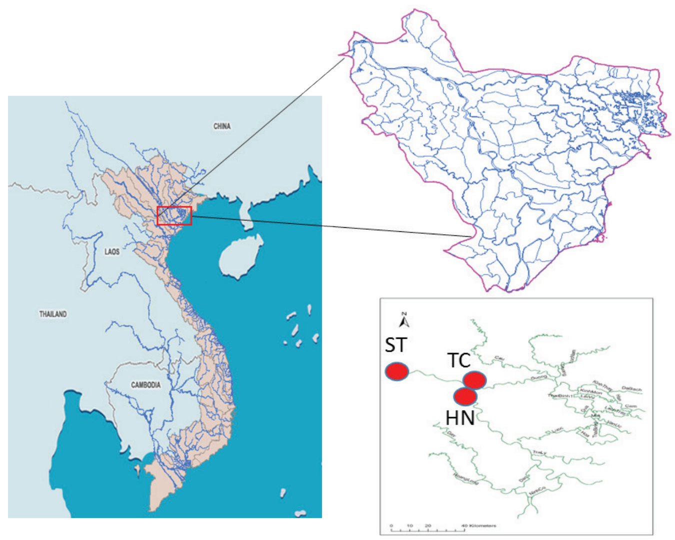

Fig. 1. Study area and location of the three stations.

Data

Table 1. Location, date, and sources of data in 3 stations in RRD.

Station	Longitude	Latitude	Data product	Date (month-day-year)	Source
ST	21.15	105.50	Daily discharge	1/1/2012-12/31/2013	VAWR
			Daily suspended sediment	1/1/2012-12/31/2013	VAWR
			Daily MODIS band 1	1/1/2012-12/31/2013 (182 scenes)	LP DAAC
TC	21.06	105.86	Daily discharge	1/1/2012-12/31/2013	VAWR
			Daily suspended sediment	1/1/2012-12/31/2013	VAWR
			Daily MODIS band 1	1/1/2012-12/31/2013 (171 scenes)	LP DAAC
HN	21.01	105.85	Daily discharge	1/1/2012-12/31/2013	VAWR
			Daily suspended sediment	1/1/2012-12/31/2013	VAWR
			Daily MODIS band 1	1/1/2012-12/31/2013 (171 scenes)	LP DAAC

Table 1 shows the location, date, and sources of all data from the three stations used in this study. The daily discharge and daily suspended sediment concentration data from the three stations were obtained from the Vietnam Academy for Water Resources (VAWR) over the course of two years: 2012 and 2013. Basically, they are measured in the middle of the river at 0.5 m, 1 m, and 3 m from the water's surface then the average values are taken. Moreover, one specific objective is to explore the relationship between R and other hydrological factors that do not depend on time, thus the period of 2012-2013 is suitable for this study. On the other hand, the reflectance data was extracted from MODIS Surface Reflectance (code: MOD09). In general, MOD09 is a seven-band product computed from MODIS level 1B land bands 1 (620-670 nm), 2 (841-876 nm), 3 (459-479 nm), 4 (545-565 nm), 5 (1230-1250 nm), 6 (1628-1652 nm), and 7 (2105-2155 nm). Most satellite data processing systems recognise five distinct levels of processing. Level 0 data is raw satellite feeds. Level 1 data has been radiometrically calibrated but not otherwise altered. Level 2 data is level 1 data that has been atmospherically corrected to yield a surface reflectance product. Level 3 data is level 2 data that has been gridded into a map projection and usually has also been temporally composited or averaged. Finally, level 4 data are products that have been put through additional processing. Due to the available data and the objective of our research, the images from MODIS Terra band 1 (620-670 nm, 250-m resolution and Surface Reflectance daily level 2 global (MOD09GQ)) is downloaded from USGS freely, then this data was input and extracted by ArcGIS software for retrieval of R from the pixel of the station's location. In this study, only the reflectance on a cloud-free day with less than 0.2 cloud fraction are acquired at the observation point of the gauged station and used for regression analysis. In total, 167 Terra MODIS images were acquired over two years for assessing the reflectance in TC and 171 images and 182 images were downloaded to use for HN and ST, respectively, from the beginning of 2012 to the end of 2013.

Methods

To estimate the possible relationship between Q-SSC, R-SSC, R-Q, and L-Q, we apply the single regression analysis to the reflectance values, observed Q, and observed SSC on the same day the MODIS images were taken. The total sediment load is calculated by the multiplication of Q and SSC as shown in Eq. (1):

$$L=Q*SSC \tag{1}$$

The performance of the regression model was checked by the coefficient of determination.

Results and discussion

Time series analysis of Q, SSC, L and R

The temporal change in Q, SSC, and L are described in Figs. 2, 3, and 4. In general, the trends of Q and SSC during the time are similar to all stations, that is, increasing during the first half of the year and decreasing during the remaining time. From Fig. 2, because ST is positioned upstream, Q in ST is equal to the sum of Q in TC and HN due to water balance of the river system. In addition, Q at all 3 stations had a similar pattern; increasing from the beginning of the year and reaching a peak of about 9000 m^3/s in September, then a decrease to just over 1000 m^3/s until the end of the year.

From Fig. 3, each station had a different temporal pattern of SSC change. The SSC in TC was highest compared to other stations although it is located in the distributary and ST is in the upstream of the river network system.

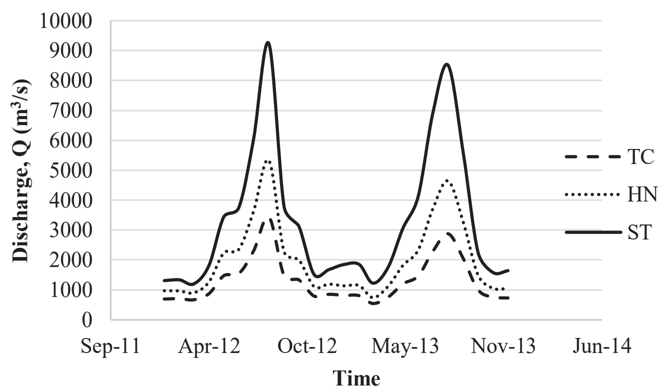

Fig. 2. Temporal change in discharge, Q, at the three stations TC, HN, and ST.

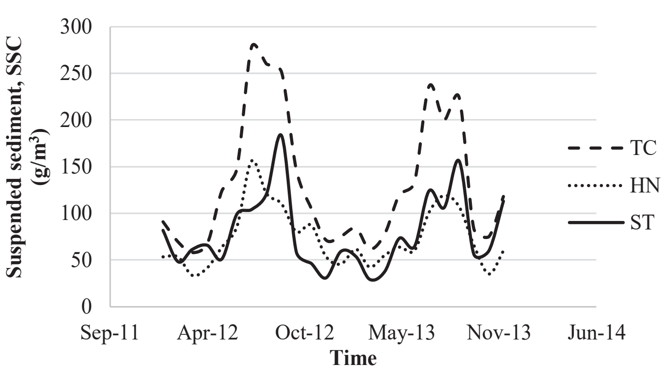

Fig. 3. Temporal change in suspended sediment, SSC, at the three stations TC, HN, and ST.

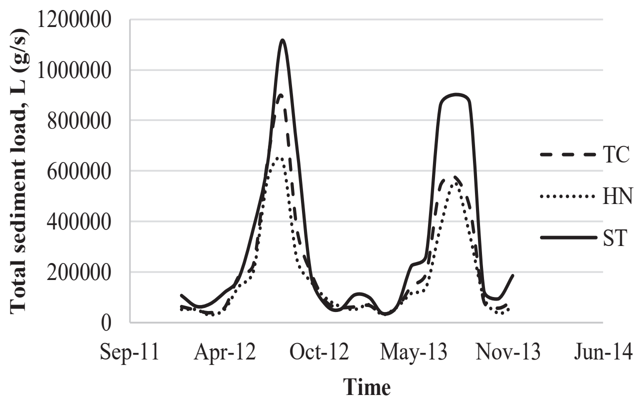

Fig. 4. Temporal change in total load, L, at the three stations TC, HN, and ST.

As shown in Eq. (1), the total load, L, (Fig. 4) is the product of discharge, Q, (Fig. 2) and suspended sediment, SSC (Fig. 3). The discharge at TC, on average, makes up approximately 45% of Q at ST. However, the total load, L, at TC is about 78% of L at ST during 2012 due to a dramatic increase in SSC at TC (Fig. 3). It is noted that SSC does not follow the balance term because of bank erosion or landslides along the river. However, the total sediment load seems to satisfy the general principle of mass balance: L at ST is equal to the sum of L at TC and L at HN. Moreover, the load of suspended sediment was higher in the rainy season than in the dry season.

Regression analysis

Due to the effects of clouds on the reflectance value, we eliminated several points at each station for a total of 24 data points over 2 years for monthly regression analysis. Fig. 5 through Fig. 8 show scatter plots of the relationships between L-Q, Q-SSC, R-Q, and R-SSC. The results of the relationship equations and performances of the regression analyses are represented in Table 2. The best fit results for all the relationships in our study followed a power function.

From Table 2, a significant overall relationship between total load, L, and discharge, Q, was observed with a high value of R^2 that was greater than 0.8 at all stations. The fit parameters of the three fit equations, in this case, were also similar. For example, the scaling factor and exponent parameters ranged from 0.23 to 1.26 and 1.49 to 1.86, respectively. Thus, in future studies, the relationship between L and Q can be defined by a single equation for the three stations.

The fit results also showed a very close connection between Q and SSC at the TC station while HN and ST had a lower performance regression compared to TC. However, the scaling factors found from the three relationship equations were very different from each other with the smallest value of 19.87 and largest value of 116.53 due to a wide range of both Q and SSC at each location (see Figs. 2 and 3). In contrast, there was only a slight difference in the value of the exponent in the relationship equation of Q-SSC.

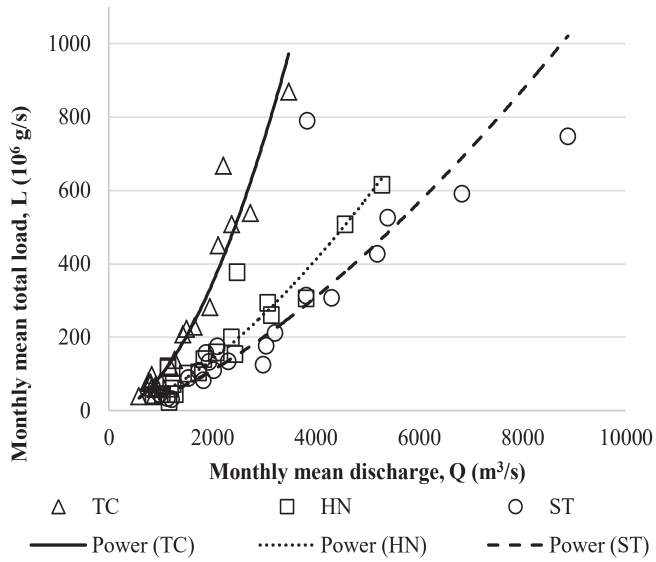

Fig. 5. Scatter plots of monthly mean total load, L, and monthly mean discharge, Q, at the three stations TC, HN, and ST.

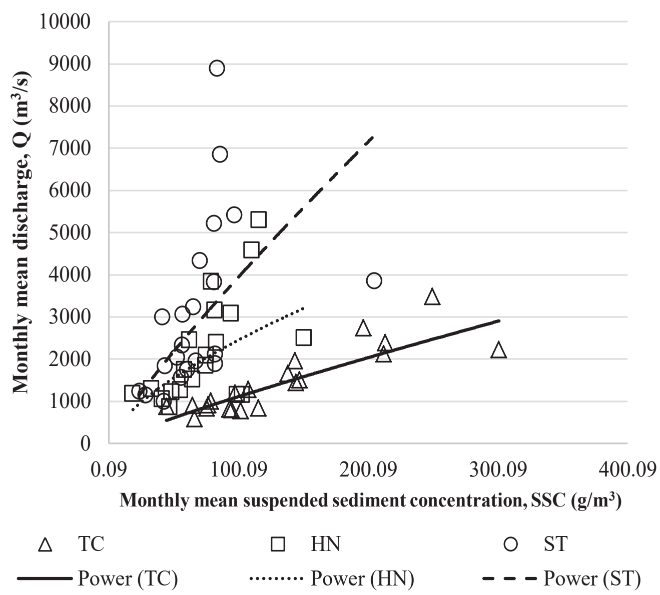

Fig. 6. Scatter plots of monthly mean discharge, Q, and monthly mean suspended sediment concentration, SSC, at the three stations TC, HN, and ST.

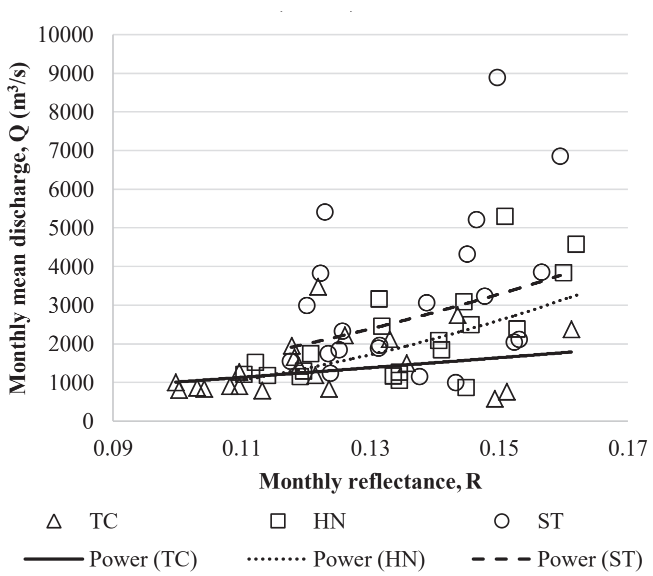

Fig. 7. Scatter plots of monthly reflectance, R, and monthly mean discharge, Q, at the three stations TC, HN, and ST.

A close relationship between R-Q and R-SSC were recorded at the HN station. The R^2 value was 0.40 and 0.33 for R-Q and R-SSC, respectively, for this station. However, TC and ST had smaller correlation results than HN. An interesting point in these results is that using the reflectance value to predict SSC is better than predicting Q by R. Both the scaling factors and exponents in the R-SSC equations were not much different for the three stations, but they did vary significantly in case of the R-Q relationship equations. The R-SSC relationship (see Fig. 8) displayed a similar trend for all stations, but there were more outlier points in TC than in HN and ST.

One possible reason to explain the outlier points is the effect of clouds. The cloud cover is different at each station and it influences the reflectance value of the pixel where the observation data was taken.

Inter-relationship between regression parameters

As shown in Figs. 5, 6, and 7, the relationship of L-Q, R-SSC, and R-Q can be expressed as

$$L=aQ^b \tag{2}$$

$$SSC=\alpha R^\beta \tag{3}$$

$$Q=\gamma R^\delta \tag{4}$$

Substituting Eq. (2) and Eq. (3) into Eq. (1) reveals

$$aQ^b = Q*\alpha R^\beta \tag{5}$$

Then,

$$Q = \left(\frac{\alpha}{a}\right)^{\frac{1}{b-1}} R^{\frac{\beta}{b-1}} \tag{6}$$

Comparing Eq. (6) with Eq. (4) gives

$$\gamma = \left(\frac{\alpha}{a}\right)^{\frac{1}{b-1}} \tag{7}$$

and

$$\delta = \frac{\beta}{b-1} \tag{8}$$

Depending on Eq. (7) and Eq. (8), it is possible to estimate the parameters for one of the three equations (Eq. (2) Eq. (3), or Eq. (4)) from the parameters of the other equations. For example, if we observed Q at a specific point of river section, we can correlate Q with satellite-observed R and then γ and δ parameter in Eq. (4) could be obtained. In addition, the parameters a and b could be possibly estimated from hydro-geological characteristics and land cover in the upstream area using a regionalization scheme [18]. Once the parameters *γ*, *δ*, a, and b are identified through the above procedure, α and β in Eq. (3) can be obtained from Eqs. (7) and (8) without using observed SSC data. Then, Eq. (3) could be applied for near-real-time SSC monitoring using satellite observed water-surface reflectance, R, and identified parameters *α* and *β*.

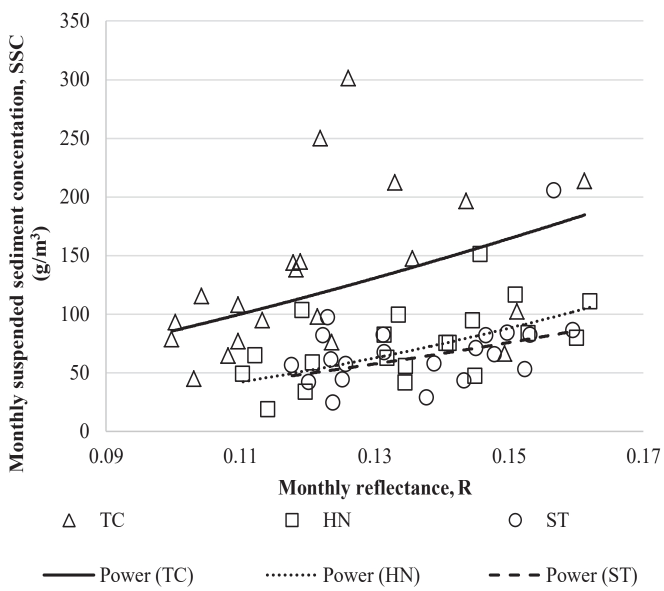

Fig. 8. Scatter plots of the monthly mean suspended sediment concentration, SSC, and monthly reflectance, R, at the three stations TC, HN, and ST.

Table 2. Relationship equation and performance of regression of L-Q, Q-SSC, R-Q, R-SSC at the three stations.

Correlation	Station	Relationship equation	R^2
L-Q	TC	$L=0.23Q^{1.86}$	0.94
	HN	$L=1.03Q^{1.55}$	0.82
	ST	$L=1.26Q^{1.49}$	0.87
Q-SSC	TC	$Q=19.87SSC^{0.87}$	0.76
	HN	$Q=116.53SSC^{0.66}$	0.37
	ST	$Q=75.42SSC^{0.86}$	0.43
R-Q	TC	$Q=1575R^{1.19}$	0.11
	HN	$Q=64678R^{2.90}$	0.40
	ST	$Q=22716R^{2.23}$	0.13
R-SSC	TC	$SSC=3427.1R^{1.60}$	0.21
	HN	$Q=7926.8R^{2.38}$	0.33
	ST	$Q=2927R^{1.92}$	0.18

Conclusions

This study explored the possibility of detecting a seasonal change of suspended sediment flux by using remotely sensed reflectance of MODIS imagery. At first, we extracted R from MODIS (band 1, 250-m resolution, Surface Daily L2G Global) and then analysed the relationship between R-SSC and R-Q. We also estimated the relationship between L-Q and Q-SSC.

The results indicate a significant relationship in L-Q and Q-SSC and a possible connection in R-SSC and R-Q. Although there were some error sources that affected the accuracy of the suspended sediment and discharge estimation, the results showed a potential of using MODIS satellite reflectance to detect SSC in the delta region. A set of equations that calculate the sediment depending on Q and R was built in this study. This set has a potential for application in other study areas where the change in Q and R corresponds to the characteristics of each area.

The approach introduced here illustrates the possible use of satellite images and the information of Q in SSC monitoring in a data-poor basin. One limitation in this study is using only R extracted from satellites, which cannot exactly detect the value of suspended sediment without Q data. However, a combination of other satellite observations such as the EOMAP (Earth Observation and Environmental Services) water quality monitoring services and R from MODIS images can solve the problem of monitoring suspended sediment in ungauged river basins in future research. Moreover, using hydrological results obtained from remote sensing can be used in combination with a numerical model for a deeper understanding about the basin.

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The authors declare that there is no conflict of interest regarding the publication of this article.

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