The Use of Sediment Rating Curve under its Limitations to Estimate the Suspended Load

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ABSTRACT

The suspended sediment load in river water is an important index for the soil erosion rate in the watersheds of designated rivers. Amongst the various methods for estimating the suspended sediment load, the most frequently used one is the sediment rating curve. The sediment rating curve can aid in the understanding of the relationship between the behaviour of the suspended sediment transport and the discharge flow for estimating soil erosion. However, the rating curve tends to underestimate the actual values of both the suspended sediment load and the suspended sediment concentration during high discharge and to overestimate them during low discharge. The aim of the present paper is to confirm how to use the sediment rating curve to estimate soil erosion under its limitations and benefits.

The accuracy of sediment rating curve is affected by various factors, including seasons, discharge stages, catchment area, and sampling frequency. In many cases, it cannot be concluded easily that sediment rating curve is the best method to estimate suspended sediment load. At the same time, there is no other method that is simple and commonly used for the estimation of suspended sediment load, as the sediment rating curve. Efforts on the improvement of the sediment rating curve, such as data separation among the seasons and the increasing of sampling frequency, are needed for the better estimation as well as the accuracy of suspended sediment load.

Keywords

hysteresis, river sediment, river sediment-discharge relationship, sediment rating curve, sediment load, soil erosion

Introduction

The suspended sediment load is defined as the fine materials that are transported and settle down in water bodies by the action of wind, ice or water (Li et al., 2018). Fluvial sediments transported in river water are divided into three types, as shown in Figure 1, namely, the bed load, the suspended sediment load, and the wash load.

The bed load originally consists of two processes, traction and saltation. Large rocks flow due to the high discharge by rolling and sliding in the traction process, whereas cobbles, pebbles and sands hop and bounce in the saltation process. However, there are some fine particles that stay in the suspension process; they are the suspended sediment load and the wash load. The suspended sediment load commonly consists of fine particles such as sand, silt, and clay. On the other hand, the wash load consists of the finest particles in the sediment that suspends in water. They are regarded as a non-capacity load and cannot be well predicted by the sediment transport model (Asselman, 2000; Heng and Suetsugi, 2014).

The suspended sediment load is considered to be an important index of the soil erosion rate in the watersheds of the rivers (Wang et al., 2013, Girolamo et al., 2015). Amongst the various methods for estimating the suspended sediment load, the most frequently used one is the sediment rating curve (SRC), which expresses the empirical relationship between the river discharge (Q) and the suspended sediment concentration (SS) or the suspended sediment load (L) (Sadeghi et al., 2008a; Wang et al., 2013; Hassan, 2014; Warrick, 2015; Unes et al., 2015).

The SRC has been used to estimate the suspended sediment concentration or the suspended sediment load for more than half a century, since the 1960s. The SRC is usually used by engineers to construct continuous time series of the suspended sediment concentration or the suspended sediment load, continuous pollutants graphs and floodplain mapping, storage variations, hydraulic designs, catchment routing, and damage assessments (Singh et al., 2014).
Fig. 1 Simple image of sediment transport model

1: Large rocks or boulders (more than 256 mm) flow by the traction process through rolling and sliding movements

2: Cobbles, pebbles and sands (0.0625 to 256 mm) are transported by the saltation process which consists of hopping and bouncing movements

3 and 4: both suspended (0.004 to 0.0625 mm) and wash loads (less than 0.004 mm) are moved by the suspension process

In addition, the SRC is also used to study erosion and depositional environments (Syvitski et al., 2000). Since there are difficulties in obtaining detailed observed suspended sediment concentration data, the SRC is sometimes utilized to estimate the missing data in order to describe the average relationship of the suspended sediment and the river discharge (Fang et al., 2015). Few suspended sediment load samples are available due to the high costs, technical constraints, and difficulties involved with accessing the designated areas (Atieh et al., 2015).

It is considered that the SRC can provide acceptable predictions of the suspended sediment concentration and the suspended sediment load (Harrington and Harrington, 2013). However, the SRC is not suitable for use as an indicator of the total hill slope erosion (Estrany et al., 2010). Nevertheless, the SRC is a simple way to assess the suspended sediment load, whenever the SS and discharge data are available (Horowitz, 2003; Sadeghi et al., 2008a; Hassan, 2014; Tananaev, 2015; Girolamo, et al., 2015; Warrick, 2015). On the other hand, while the SRC can be conveniently used to estimate the amount of suspended sediment load in a river, there are limitations in using it to predict the soil erosion rate.

Most SRCs tend to underestimate the suspended sediment concentration during high discharge and overestimate it during low discharge (Horowitz, 2003; Boukhrissa et al., 2013). Moreover, the predicted suspended sediment load tends to be more underestimated than the observed suspended sediment load (Asselman, 2000; Heng and Suetsugi, 2014; Girolamo et al., 2015). Although some articles have addressed its limitations, no comprehensive reviews of the SRC have been conducted yet. Thus, this paper will focus on clarifying how the SRC can be used and what its limitations are.

Characteristics of Sediment Rating Curve

1. Types of sediment rating curves

As mentioned above, the SRC expresses the suspended sediment concentration as a function of the discharge. The most frequently used equation for the SRC is written in the form of a power function, as follows:

\[ SS = a \times Q^b \]  

Equation (1) shows the relationship between the sediment concentration and the discharge, and equation (2) shows the relationship between the load and the discharge. To estimate empirical parameters \( a \) and \( b \) of the sediment rating curve, the most commonly used method is the log-transformation of equation (1) or equation (2). By taking a logarithm of both sides of equation (1), the following linear equation will be obtained:

\[ \log(SS) = \log(a) + b \log(Q) \]

Then, the values for parameters \( a \) and \( b \) can be obtained by a normal linear regression analysis. The same method can be applied to equation (2).
Fig. 2 Review of SRC past studies based on 32 references selected

a: Percentage of equation types used for SRC (40 cases), 70% from the total equation using power function, 59% amongst them were based on suspended load data, and the rest were based on suspended sediment concentration data

b: Left: Percentage of how long the study had been conducted (37 cases) Right: Percentage of how long the data were obtained during the study to make SRC (45 cases)

c: Percentage of separation used for making SRC equation (48 cases); using completed data without any separation, rising or falling stage separation, seasonal separation, and high and low discharge separation

d: Percentage of the total watershed area where the studies were conducted (39 cases)

e: Number of land uses mentioned in the references regarding the SRC applied (19 references)
Figure 2a shows that the power function regression in equations (1) and (2) is the most frequently used equation form (70%). The other forms, such as linear regression (7%), polynomial regression (8%), and other modified equations (15%), can potentially be used for the calculation.

Moreover, in Figure 2a, it is seen that the number of researchers using the suspended sediment load (66%) to generate the power regression SRC exceeds that using the suspended sediment concentration (34%). This means that most studies have been focused on the sediment supply rather than the sediment pattern. The sediment load has been widely used to understand the erosion rate and the sediment supply, while the suspended sediment concentration has been used to understand the sediment pattern and the hysteresis loop. Meanwhile, the used suspended sediment load data consist of mean load data taken during the discharge sampling intervals.

Employing the mean suspended sediment load and the mean discharge enables the avoidance of problems associated with logarithmic transformation, such as the high frequency of the low suspended sediment concentration data which can reduce the SRC accuracy (Jansson, 1996).

2. Hysteresis loop

Hysteresis is the time lag between the peak discharge (Q) and the peak sediment concentration (SS) (Heng and Suetsugi, 2014), represented by a hysteresis loop. The hysteresis loop indicates the behaviour of the suspended sediment in watercourses as a function of the energy conditions through the discharge of water (Baka, 2008) during rainfall events (Fang et al., 2015). The dynamics of erosion and the suspended sediment load might be reflected in the hysteresis loop. The hysteresis loop for one river could be different from those for other rivers. This is because the relationships are extremely complicated and depend on the river characteristics, water years, and rainfall events (Lloyd et al., 2016).

The suspended sediment transported by runoff commonly represents a mixture of sediment derived from different locations and sources within a specific catchment (Carter et al., 2003). Lloyd et al. (2016) reported that the hysteresis loop has been used as one of the tools to compare rainfall events among catchments.

![Sample of hysteresis loops](image)

Specifically, Higgins et al. (2016) outlined that there were four factors affecting hysteresis loops. They are extreme changes in the flow produced by a sudden increase in rainfall, the availability of sedimentary material in riverbeds that can easily be removed by runoff, the interaction of deep soil layers with high silt and clay contents, which are strongly bonded and resistant to runoff, and aggressive flooding that causes the damming of sediment in flood plains upstream of a gauging station. In general, it can be concluded that rainfall patterns, land use, soil characteristics, climate, erosion, and the geomorphology of a river are the reasons behind the variations in sediment concentrations which differ from peak to peak (Jansson, 1996; Yan and Lee, 2017).
To get to know more about hysteresis loops, Williams (1989) classified five common classes of hysteresis loops, namely, the single-valued line (straight or curved line), a clockwise or positive loop, a counter-clockwise or negative loop, a single-valued line plus a loop, and a figure-8 loop, whereby each type represents a different condition of the water discharge and suspended sediment concentration. Among the types, clockwise and counter clockwise are the most typical loop patterns in the hysteresis between the suspended sediment concentration and discharge relationship.

A clockwise loop (Figure 3a) occurs when the suspended sediment concentration peak arrives before the discharge peak. It represents that there is a quick flushing of the suspended sediment which may become exhausted at the end of a rainfall event, controlled by the sediment depletion during a rainfall event (Baca, 2008). A clockwise loop mostly occurs in small headwater catchments when the sediment area is short (Fang et al., 2015), as well as during dry and transitional seasons (Higgins et al., 2016).

3 Physical interpretations of the parameters

3.1 Importance of the power law

While some researchers have insisted that it is difficult to give physical meanings to parameters a and b (Asselman, 2000; Hassan, 2014) of the SRC, others have attempted to obtain a physical interpretation of these parameters. Generally, it is a very significant finding that any phenomenon which can be described or approximated by the power law can be considered to have some physical meaning (Asselman, 2000).

Although sometimes the power function cannot provide an appropriate approximation of the sediment rating curve, most researchers generate it in order to estimate both suspended sediments, namely, concentration and load (i.e., Walling, 1977; Asselman, 2000; Fan et al., 2012; Guzman et al., 2013a; Harrington and Harrington, 2016; Hassan, 2014; Heng and Suetsugi, 2014; Girolamo et al., 2015). Thus, it is worthwhile to consider the physical meaning of both parameters, so that the relationship between the suspended sediment and the discharge can be correctly understood.

3.2 Parameter a

Parameter a refers to the erosion severity index which is influenced by the soil erodibility related to river catchment characteristics such as topographic relief and runoff (Syvitski et al., 2000; Warrick, 2015). Syvitski et al. (2000) also argued that measured value of parameter a has a negative correlation with the mean discharge ($R^2 = 0.63$), catchment relief ($R^2 = 0.39$), and flow duration ($R^2 = 0.29$). However, it has a positive correlation with the mean annual air temperature.

In addition, high parameter a values represent intensively weathered materials (Yang et al., 2007; Hassan, 2014), as well as a large amount of fine materials in the suspension (Higgins et al., 2016), which can be easily transported in the river.

3.3 Parameter b

Parameter b is an index of an erosive river and reflects the new sediment that becomes available when the discharge increases (Yang et al., 2007; Hassan, 2014; Heng and Suetsugi, 2014). It is affected by the grain size distribution of the available material. On the contrary of parameter a, parameter b has a negative correlation with the temperature and positive correlation with the mean discharge and catchment relief (Syvitski et al., 2000). The high parameter b values indicate a river that has increasing erosion and transport power along with increasing discharge (Yang et al., 2007; Higgins et al., 2016).

Factors Affecting the Rating Curve Accuracy

1. Rainfall pattern

The suspended sediment behaviour in a watercourse is a function of the energy condition which causes the sediment to be stored during a low flow and then transported when the flow increases to a high flow. Guzman et al. (2013b) stated that high sediment under a low flow can be found at the beginning of a rainy stage, and low sediment under a high flow can be found at the end of a rainy stage.

The suspended sediment concentration does not always increase with an increase in discharge, as shown by the hysteresis loop in Williams (1989) expressed on the Figure 3. SS concentrations during the rising limb reflect a prolonged increase in the sediment supply along with an increase in the discharge flow from the catchment area. On the other hand, SS concentrations during the falling limb could be produced by bank cutting and collapses near the measuring location (Fan et al., 2012).
Rainfall is the most important factor controlling the amount of suspended sediment concentration in a small catchment (Estrany et al., 2009; Tuset et al., 2016). There is a relationship between rainfall kinetic energy and sediment transport, for which rainfall is the driving force of most of the water erosion process and the creation of surface runoff (Lin and Chen, 2012).

During rainfall events, the raindrops strongly impact soil dispersion which leads to soil loss. Rainfall significantly increases the flow resistance and rill erosion by the discharge increase (Tian et al., 2017). In addition to rainfall, in cold regions, snowfall could bring about the needle ice phenomenon on the ground surface which can easily melt when the temperature rises and can produce surface runoff during sunlight periods (Renard et al., 1997; Tran, 2014).

The rainfall duration also affects the erosivity factor. Even though the runoff volume increases as the rainfall duration grows longer, there is an insufficient capacity for the runoff to transport all the sediment to the outlet (Katebikord et al., 2017). This means that more sediment cannot be transported easily under the condition of longer rainfall duration. Horowitz (2008) stated that the suspended sediment concentration is a matter of sediment supply rather than a matter of a change in the discharge flow, so that changes in the suspended sediment concentration are mainly caused by increases in the sand and silt fractions during the increase in discharge. It can be concluded that longer rainless periods will be accompanied by more available sediment and the occurrence of higher concentrations of suspended sediment.

2. Dataset length and sampling frequency

The accuracy of the SRC depends on the fitting of the equation (linear, power, polynomial, or modified equations) as well as the datasets collected and the watershed characteristics which affect the sediment transport (Ahanger et al., 2013). The SRC can generate suspended sediment loads, which are generally poor and lead to underestimation (Ide et al., 2009). The SRC produces about ≤15-20% accuracy, according to Ndomba et al. (2009), and tends to underestimate as much as approximately 73% during periods of high flow and overestimate as much as approximately 224% during periods of low flow (Lin, 2006). Moreover, Wang et al. (2013) declared that the SRC underestimates low SS concentrations and overestimates high SS concentrations. Data uncertainty, such as measurement errors and low sampling frequency, could be the reason behind the low accuracy, especially for measurements taken in mountainous upstream areas (Heng and Suetsugi, 2014).

Although it is difficult to achieve, ideally, some articles recommend that the SRC needs a sampling period of more than 10 years and also that daily obtained data should be used to obtain an acceptable level of accuracy (Figure 2b). On the other hand, for the small-scale rivers mentioned in Table 1, the ordinary SRC cannot be directly applied, since sporadic precipitation events may have a large impact and affect the sediment transport (Tfwala and Wang, 2016). Generally, continuous sampling at short intervals such as average hourly data will improve the time series analysis to produce better results for the SRC (Mount and Abrahart, 2011; Tananaev, 2015). In order to obtain a better SRC, the monitoring of the suspended sediment concentration should be done during heavy rain events (Ide et al., 2009).

### Table 1: River classification based on discharge characteristics, drainage areas, and river widths

| River size   | Drainage area [km²] | Average discharge [m³/s] | River width [m] | Stream order* |
|--------------|---------------------|--------------------------|-----------------|---------------|
| Brook        | < 10                | < 0.1                    | < 1             | 1 to 3        |
| Small stream | 10 - 100            | 0.1 - 1.0                | 1 - 8           | 2 to 5        |
| Stream       | 100 - 1,000         | 1 - 10                   | 8 - 40          | 3 to 6        |
| Small river  | 1,000 - 10,000      | 10 - 100                 | 40 - 200        | 4 to 7        |
| River        | 10,000 - 10⁵        | 100 - 1,000              | 200 - 800       | 6 to 9        |
| Large river  | 10⁵ - 10⁶           | 1,000 - 10,000           | 800 - 1,500     | 7 to 11       |
| Very large river | > 10⁶                | > 10,000                 | > 1,500         | > 10          |

*in average number proposed by Chapman ed. (1996)

The average daily data for the suspended sediment sampling has recently become the most widely used method for generating the SRC (Higgins et al., 2016). In addition, the average annual data sets are often used for long-term estimation of more than 10 years for large-scale rivers. However, there are some researchers who derived SRCs from average weekly data sets (e.g., Sadeghi et al., 2008a; Ide et al., 2009), average monthly data sets (e.g., Hu et al., 2011; Zhang et al., 2012; Wang et al., 2013,) or average hourly data sets during rainfall events (e.g., Curtis et al., 2006; Baca et al., 2008; Ide et al., 2009; Fang et al., 2015; Rovira et al., 2015), as
shown in Figure 2b. Bulk sampling for suspended sediment had been done for large-scale rivers. Suspended sediment is usually transported during extreme rainfall events with a high discharge flow.

Direct sampling of the suspended sediment in a river is the correct thing to do; however, it is difficult to do this during extreme rainfall for safety reasons (Tfwala and Wang, 2016). In relation to this reason as well as the distance and limitations of certain locations, a single-sampling point using automatic sediment sampling becomes an option (Horowitz, 2008). An automatic water sampler is often installed at the edge of an outlet with one litter sampling bottles to measure the suspended concentration.

During storm events, water will be taken at specific intervals (mostly hourly). Thereafter, water samples will be filtered, air-dried, and weighed to determine the mass of the sediment captured per litter of discharge. In addition, collecting at a single sampling point is not a good method to generate a representative suspended sediment concentration for a whole watershed area. The SRC is used to reflect the medium- and short-term changes in sediment transport at the basin scale (Higgins et al., 2016). In conclusion, the time interval should be correct, whether it be hourly, daily, weekly or monthly, in order to strengthen the accuracy of the SRC.

Monthly data leads to stronger $R^2$ in larger areas and daily data leads to the weakest $R^2$ in narrow areas due to the suspended sediment based on the SRC (Figure 4b-left). On the other hand, for the suspended load based on the SRC, the annual data interval leads to stronger $R^2$ in large areas, whereas weekly data leads to the weakest $R^2$ in narrow areas due to the suspended load based on the SRC (Figure 4b-right).

Moreover, it is likely that using monthly suspended sediment concentration data for generating the SRC will produce the better $R^2$ value. However, by generating annual suspended load data, a better $R^2$ value can be produced for long-term sampling periods (more than 10 years). On the other hand, daily suspended load data produce better accuracy for completing the research within a year.
3. Dataset separation

Even if long-term data is obtained, the suspended sediment concentration frequently shows large scatter against the discharge (Asselman, 2000). This scatter is attributed to the spatio-temporal variation in the erosion rate which is reflected in the hysteresis loop having increasing and decreasing suspended sediment concentrations scattered during both rising and falling limbs, respectively (Tran, 2014). In addition, the fluctuating pattern in the sediment concentration was seen during both limb periods, thus creating the large scatter. In order to improve accuracy of SRC, some studies attempted to separate the SRC for different seasons and stages according to the flow duration curve. Other studies divided the SRC based on different conditions, such as humid and dry climates (Talebi et al., 2015), temperature stages (Toth and Bodis, 2015), organic and inorganic suspended sediment concentrations (Rovira et al., 2015), etc. However, most of the studies were still able to obtain the SRC without any separation (Figure 2c).

Since there are seasonal differences amongst the countries of the world, there will be many sediment patterns reflected on their own hysteresis loops. Higgins et al. (2016) spelled that out for the Magdalena River, Columbia where there are many changes in the suspended sediment movement pattern during one hydrological year. It is mentioned that from the end of the first rainy season (May to June), both the discharge and the suspended sediment concentration increased.

During the snowmelt period and the spring season (March to June), high discharge appeared as the most active hydro-sediment load process. Due to the snow melting process, the soil is potentially capable of breaking up the surface layer of the riverbank, which results in an increase in the availability of the fine materials and the generation of channel erosion (Ide et al., 2009). However, at the beginning of the transitional season (June to July), there was a decreasing process for either the discharge or the suspended sediment concentration.

Still continue on Magdalena River study case, start from the end of the transitional season to summer (July to August), both the water discharge and the suspended sediment concentration decreased because of the effect of the rainless period. At the beginning of the second rainy season (August to October), both conditions increased. Moreover, during the summer period (July to October), it was the largest suspended sediment concentration of the annual period due to more flood occurrences associated with the high rainfall intensity.

Successive rainfall events transport a lesser amount of suspended sediment concentration than prior rainfall events. Thus, the available sediment decreases during the prior rainfall events. That is why the prediction of the annual suspended sediment load may be affected by the antecedent rainfall history (Ide et al., 2009). At last, during the second rainy season and until the beginning of winter (October to December), the condition becomes varied. This is why the separation of the SRC, based on the season, is also important.

Another argument by Guzman et al. (2013a), after several studies had been conducted on sub-humid Ethiopian highlands, was that a high suspended sediment concentration combined with a low discharge flow could be found at the beginning of each rainy season. On the contrary, a high discharge brought a low suspended sediment concentration at the end of each rainy season.

In addition, Sadeghi et al. (2008b) stated that in a Japanese cypress forest, a higher suspended sediment concentration could be found during intense rainfall events and a lower concentration during less intense rainfall events. It can be concluded, therefore, that the important factor in characterizing the changes in the sediment concentration during rainfall is the period of shifting from high to low concentrations.

Different patterns were observed in the United Kingdom by Collins et al. (1998), who stated that to get a better understanding of the sediment movement using the SRC, the sampling period should be divided into winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and autumn (September, October, and November) events. As an example, Harrington and Harrington (2013) separated the rating curves into five periods: all data in general, the summer period, the winter period, during the rising stage, and during the falling stage. Moreover, Zheng et al. (2018) suggested making separation data based on the combination of seasons and stages, as well as separation data based on the discharge levels, so that the errors could be minimalized by improving the R² value (Walling, 1977; Heng and Suetsugi, 2014; Warrick, 2015; Fang et al., 2015; Tuset et al., 2016).

4. Watershed area

Rivers can be classified based on their discharge characteristics, drainage areas, and river widths, classified by Chapman ed. (1992) as is written in Table 1. Most of the research conducted on suspended sediment measurement has been done on large rivers (Guzman et al., 2013b). Many researchers focused on large river channels to measure the soil erosion processes, sediment dynamics, suspended sediment load evaluations, etc. However, only a few studies addressed the suspended sediment transport on small streams.
(Girolamo et al., 2015), and only 9% of the research was conducted on brooks, which were mostly located in Japan (Figure 2d) (Baca, 2008; Sadeghi et al., 2008a; Ide et al., 2009).

Figure 4a shows that there are no clear relationship or pattern for the suspended sediment concentration data within the watershed area for the performance of the $R^2$ values. On the other hand, by generating suspended sediment load data, the wider the watershed area, the higher the resulting $R^2$ value; this means that more accurate SRCs could be produced. Thus, it is confirmed by Table 3 that there is a distant relationship between the sampling interval and the watershed area. In other words, wider watersheds lead to smaller temporal changes in the suspended sedimentation due to the long concentration time, and longer sampling intervals will result in better accuracy of the SRC. On the contrary, narrower watersheds lead to larger temporal changes in the suspended sedimentation. Thus, shorter sampling intervals are needed.

| River Class | Country | River name | SRC equation | Data sampling method | References |
|-------------|---------|------------|--------------|----------------------|------------|
| Brook River | Japan | Ochozu catchment brooks | $L = a Q^{b+1}$ and modified regression | weekly | Ide et al. (2009) |
| | | Hinotani Ike catchment brooks | $SS = a Q^b$ | weekly | Sadeghi et al. (2008) |
| | Slovakia | Vah River (Rymbark catchment) | $L = a Q^{b+1}$ | hourly (annually summary) | Baca (2008) |
| Small Stream | Taiwan | Shiwen River | $L = a Q^{b+1}$ | hourly during typhoon | Tiwala and Wang (2016) |
| | China | Yungxiogou catchment streams | $SS = a Q^b$ | daily | Fang et al. (2015) |
| | | Yarlung Zharbo River catchments | $L = a Q^{b+1}$ | daily | Zheng et al. (2018) |
| Stream | Algeria | El Kebir River | $SS= a Q^b$ and $L= aQ^{b+1}$ | annually | Boukrissa et al. (2013) |
| | India | Lokapavani River | $(a Q^b)^{1/(1-b)}$ | daily | Shima and Ramu (2016) |
| | USA | Rio Chama River | $L = a Q^{b+1}$ | daily | Ghorbani et al. (2013) |
| | | Calleguas Station catchment streams | $L = a Q^{b+1}$ | daily | Kisi (2007) |
| | Iran | Nahremian catchment streams | $L = a Q^{b+1}$ | monthly | Talebi et al. (2015) |
| | | Shazan catchment streams | $L = a Q^{b+1}$ | daily | Khaleedian et al. (2017) |
| | | Bazeneh catchment streams | $L = a Q^{b+1}$ | daily | |
| | Ireland | Bandon River Owenabue River | $SS = a Q^d$ and $SS = c Q + d$ | annually | Harrington and Harrington (2013) |
| | Hungary | Danube River | $(SS$ (polynomial regression and linear regression) | daily | Toth and Bodis (2015) |
| | Costa Rica | Reventazon River | SS (modified equation) | daily | Jansson (1996) |
| | China | Red River (Nam Muc catchment) | $L = a Q^{b+1}$ | monthly | Wang et al. (2013) |
| | | Middle Yellow River | $L = a Q^{b+1}$ | annually | Gao et al. (2017) |
| | Iran | Pool Dab catchment | $L = a Q^{b+1}$ | monthly | Talebi et al. (2015) |
| | India | Marun River | $L = a Q^{b+1}$ | annually | Bordbar and Fuladipanah (2014) |
| | USA | Upper Yuba River | $SS = a Q^b$ | daily and annually | Curtis et al. (2006) |
| | | Broad River | SS (polynomial regression and linear regression) | daily | Horowitz (2003) |
| | Ethiopia | Lake Tana catchment rivers | $L = a Q^{b+1}$ | annually | Moges et al. (2016) |
| | | Blue Nile sub-catchment rivers | $L = a Q^{b+1}$ | annually | Ali et al. (2014) |
River

| Country      | River (Catchment)                        | Equation | Time scale | Reference            |
|--------------|-----------------------------------------|----------|------------|----------------------|
| China        | Red River (Da catchment)                | $L = a Q^{b+1}$ | monthly    | Wang et al. (2013)   |
|              | Middle Yellow River (Wuding catchment)  | $L = a Q^b$   | annually   | Gao et al. (2017)    |
| Ethiopia     | Blue Nile sub-catchment rivers          | $L = a Q^b$   | annually   | Ali et al. (2014)    |
| Brazil       | Doce River                              | $L = a Q^{b+1}$ | daily      | Oliveira and Quaresma (2017) |
| Spain        | Ebro River                              | $SS = f e^{aQ}$ | hourly     | Rovira et al. (2015) |
| Russia       | Anabar River                            | $SS = a Q^b$   | annually   | Tananaev (2015)      |
| USA          | Skunk River                             | $SS = a Q^b$   | daily      | Unes et al. (2015)   |
|              | Oconee River                            | $SS = a Q^b$   | daily      | Horowitz (2003)      |
| Europe       | Rinne River (Rheinfelden and Maxau points) | $SS = a Q^b$   | annually   | Asselman (2000)      |
| China        | Chianjiang River (Middle and Downstream) | $SS = a Q^b$   | monthly    | Hu et al. (2011)     |
|              | Red River (Chiang Sean catchment)       | $L = a Q^{b+1}$ | monthly    | Wang et al. (2013)   |
|              | Middle Yellow River (Hekou Longmen catchment) | $L = a Q^{b+1}$ | annually   | Gao et al. (2017)    |
|              | Yellow River                            | $SS = a Q^b$   | daily (annually summary) | Fan et al. (2012)   |
| Large River  |                                            |           |            |                      |
| Europe       | Rinne River                             | $SS = a Q^b$   | annually   | Asselman (2000)      |
| Cambodia     | Lower Mekong River (Tonle Sap catchment) | $L = a Q^{b+1}$ | monthly    | Heng and Suetusi (2013) |
| Vietnam      | Lower Mekong River (Sre Pok catchment)  | $L = a Q^b$   | monthly    | Heng and Suetusi (2014) |
| Russia       | Lena and Indigirka Rivers               | $SS = a Q^b$   | annually   | Tananaev (2015)      |
|              | Sukhaya Elizovkaya River                | $SS = a Q^b$   | daily      | Mouri et al. (2014)  |
| Iraq         | Tigris River                            | $SS = a Q^b$   | hourly     | Hassan (2014)        |
| Very Large River |                                        |           |            |                      |
| China        | Pearl River                             | $SS = a Q^b$   | annually   | Zhang et al. (2012)  |
|              | Upper Chianjiang River                  | $SS = a Q^b$   | monthly    | Hu et al. (2011)     |

Table 3: Percentage of sampling intervals against the watershed area, conducted on 67 watersheds from 32 selected references

| Area (km²) | Hourly (%) | Daily (%) | Weekly (%) | Monthly (%) | Annually (%) |
|------------|------------|-----------|------------|-------------|--------------|
| >1000       | 0          | 16.7      | 0          | 43.8        | 39.6         |
| 1 – 1000    | 0          | 12.5      | 0          | 37.5        | 50           |
| <1          | 9.1        | 27.3      | 63.6       | 0           | 0            |

5. Errors and bias
Since all equations are approximations, error estimation is not something that is avoidable. Thus, to obtain reliable values, statistical estimation is required. The use of log-transformed power regression introduces a bias to re-transformed equations (1) and (2) (Jansson, 1996). Jansson cited Miller (1984) in proposing a correction factor to the re-transformation of a natural logarithmic regression, as follows:

Where, refers to the variance in the natural logarithm. Later on, Ferguson (1986) modified equation (4) for a base-10 logarithm, as follows:

Where, refers to a variance in the base-10 logarithm.

Regarding the bias, Ferguson (1986) proposed a way to obtain point estimates by using the following bias correction factor ($\beta$), which is called smearing factor $s^2$, as follows:

Where, subscripts $obs$ and $cal$ of $SS$ refer to the observed and the calculated suspended sediment concentration, respectively, and $n$ is the number of total observations. Sadeghi et al. (2008a) used another way to consider the bias correction factor by $\epsilon$ as the residual error between the observation and the prediction (mg l$^{-1}$), as follows:
To improve the accuracy of the SRC, Ide et al. (2009) modified the power regression by adding the antecedent rain factor, as follows:

\[
L_i = A R_i^\gamma
\]

Where, \( L_i \) is the suspended sediment load (kg ha\(^{-1}\)), \( AR_i \) is the \( i \)-day antecedent rainfall (mm), and \( \gamma \) is the empirical parameter. By introducing a kind of new weighing parameter which considers the effect of the antecedent rainfall effect, Ide et al. (2009) showed the possibility of improving the accuracy of the SRC. Apart from that, many other modified equations have been proposed by other researchers to improve the SRC accuracy.

6. Other factors affecting the accuracy of the SRC

Besides improving the equation by inputting some bias factors, some researchers have also improved the sampling technique and parameters. However, it seems better to combine the SRC analysis with a conventional prediction, such as the Universal Soil Loss Equation, to get a better understanding of the reason for using the vegetation and land use factor as well as the topography. Wang et al. (2013) stated that a common SRC without considering the temporal dynamic changes in the vegetation cover is not very reasonable and generally cannot lead to agreement with the simulation results. However, only some studies have mentioned the vegetation type of watersheds (Figure 2e). Most studies were conducted on large rivers (Figure 2c) which covered many land uses in watersheds. This leads to the complexity of relating the vegetation effect to the SRC.

Conclusions

Horowitz (2008) explained that the suspended load is a product of the water discharge, the suspended sediment concentration, and the conversion of mass and time units. The efficiency of the SRC depends on the sampling frequency, including the amount of data available to develop the rating curve and how well it represents the ranges in discharge and load at a specific site.

All the limitations of the SRC can be improved by obtaining more observed data and dividing the data on a monthly or seasonal basis (Hassan, 2014). By gathering more observed data, the wide variation in field data can be minimalized. However, a simple SRC cannot adequately represent the complex load process even in a specific catchment area. There are some ways to improve the accuracy of the SRC, including the separation of data based on seasons or stages, which were mentioned above.

Rainfall plays an important role in the relationship between the discharge flow and the suspended sediment concentration. However, the hydrological process is different from place to place. A catchment with a climate having four seasons will have different sediment transport characteristics than a monsoonal catchment. There is also the effect of the vegetation that can be seen in the entire explanation process, which is likely to be that the type of vegetation can produce different rating loops. However, the effect of vegetation on SRC is still unclear because of a limited number of studies. In conclusion, the purpose of using the SRC is to predict suspended sediment concentrations based on the storm runoff volume during the peak rainfall in a specific area within a specific period of time.

The SRC can help to describe the relationship between the behaviour of the suspended sediment transport and the discharge flow in order to help understand the water erosion. Regarding the limitations of reasonable factors in explaining the value of each parameter, it cannot be said that the SRC is not reliable for predicting the suspended load concentration in river water. However, it is likely that the SRC will work well only when sampling is done during periods of rainfall. In order to apply the SRC to all the discharge data that are acquired, however, an average daily data set would be required, not an hourly one. Besides improving the equation, by inputting certain factors, some researchers have also improved the sampling technique and calculation. There are still more efforts to improve the performance of SRCs to obtain a better understanding of the sediment movement by increasing the sampling frequency or separating datasets based on seasons or stages, particularly in upstream mountainous areas. Moreover, it seems that SRCs work better on large-scale rivers rather than smaller scale rivers.

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