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Improving sediment load estimations: The case of the Yarlung Zangbo River (the upper Brahmaputra, Tibet Plateau)

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ABSTRACT

Suspended sediment load of a river represents integrated results of soil erosion, landform change and ecosystem variation occurring within the river basin. Accurate estimation of suspended sediment load is helpful for distinguishing the impact of natural and anthropogenic factors on earth system processes within river basin under global climate change. Suspended sediment load, with long-term in-situ observation limited by harsh conditions, can be estimated by sediment rating curves and various subdivision methods with suspended sediment concentration and discharge data of low-frequency. New sediment rating curve subdivision methods based on flood ranks and suspended sediment concentration stages were proposed in this study. The flood ranks subdivision method, which defined a flood to begin when discharge exceeded the critical discharge value (rank1) or the previous peak flow (rank2 and the later), and end when fluctuating discharge reached the peak flow of current flood again (which is the beginning of next flood) or lowered to the critical discharge value (the last rank), was suitable for application in the basin where sediments were mainly transported and exhausted in early events. The suspended sediment concentration stages subdivision method, i.e. the rising and falling limbs of suspended sediment concentration separated by peak dates estimated based on accumulated precipitation, was suitable for application in the basin where soil erosion was closely related to precipitation. Compared to the traditional sediment rating curve, and seasonal, discharge classes and discharge stages subdivision methods, these newly proposed methods can improve suspended sediment concentration and subsequently suspended sediment load estimation in the middle reach of the Yarlung Zangbo River with higher coefficients of determination and Nash-Sutcliffe efficiency coefficients and lower bias and root-mean-square errors. Moreover, combination of the two separately developed methods presented further improved estimation. The newly proposed sediment rating curve subdivision methods could be helpful for suspended sediment load estimation and therefore are useful for water resource management within river basins.

1. Introduction

Suspended sediment load (*SSL*) of a river represents an integrated measure of erosion, sediment transport and deposition processes occurring within the river basin over a specified time period (Delmas et al., 2011). Transport of sediment from rivers to the ocean is one of the main pathways in the global geochemical cycle, and plays an important role in transferring sediment and associated material, including organic carbon and heavy metals (Schäfer et al., 2002; Lal, 2003; Audry et al., 2004). Change in *SSL* can induce variations of downstream channel erosion and delta sedimentation in many fluvial systems (Lu and Siew, 2006; Milliman and Farnsworth, 2011; Dai and Liu, 2013). With the increased interest in global climate and environmental change, quantitative analysis of river *SSL* is an important tool for assessing earth system processes, and for understanding the impacts of natural and anthropogenic disturbances on geomorphic processes within river basins (Vörösmarty et al., 2003; Walling and Fang, 2003).

Long term observation of *SSL*, which is estimated from water discharge (*Q*) and suspended sediment concentration (*SSC*) in rivers, is important for river basin management (Asselman, 2000). Although discharge can be measured automatically and continuously, or near-continuously (Horowitz, 2003; Delmas et al., 2011), the availability and

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reliability of *SSL* data are limited and usually with a coarse resolution because *SSC* data are mainly obtained from infrequent sampling due to the high cost of operation and maintenance of samplers. Therefore, low-frequency *SSC* data is a limiting factor in sediment dynamics research.

For rivers with harsh observation conditions, high-frequency *SSC* data are usually insufficient. Therefore, various approaches have been developed for estimating *SSC*, including averaging estimators, ratio estimators and regression methods (Quilbé et al., 2006). For averaging estimators, only the available *Q* and *SSC* data were used to estimate mean *SSL* (Walling and Webb, 1988). For ratio estimators, covariance between *Q* and *SSC* was taken into account (Beale, 1962). For regression methods, empirical relationships were established between the *Q* and *SSC*. Among the regression methods, sediment rating curve (SRC), which presents the relation between *Q* and *SSC* by linear, power, and polynomial functions, etc., have been widely applied in previous studies (Walling, 1974; Wood, 1977; Preston et al., 1989; Asselman, 2000; Vericat and Batalla, 2006; Ali and Boer, 2007; Delmas et al., 2011; Tananaev, 2013; Mei et al., 2015). The most common expression of SRC is a power function (Walling, 1974), described as:

$$SSC = aQ^b \tag{1}$$

where *SSC* is suspended sediment concentration (kg/m^3), *Q* is water discharge (m^3/s), and *a* and *b* are regression coefficients. In recent studies, the two regression coefficients were typically estimated by nonlinear least squares regression, the best fitting procedure recommended by Asselman (2000). However, the log-transformation of *Q* and *SSC* data, prior to the analysis of SRC in the power relation, could substantially underestimate actual *SSC* (Horowitz, 2003). Although the regression coefficients *a* and *b* have no physical meaning, they have often been described as index of the soil erodibility and river flow erosivity, respectively (Peters-Kümmerly, 1973; Morgan, 1995).

The traditional SRCs were based on the hypothesis that a general relation exists between *Q* and *SSC*. In reality, this relation is usually not homogeneous due to varying river basin conditions, including seasonal effect, flow dynamics, sediment availability, and anthropogenic activities (Horowitz, 2003). As a consequence, some traditional SRCs were further developed by subdividing the *Q* and *SSC* data into different groups. For example, some SRCs were grouped by seasonal classes (Walling, 1977), by discharge classes (e.g. low, normal and high flow) (Preston et al., 1989; De Girolamo et al., 2015), by discharge stages based on rising and falling limbs (Delmas et al., 2011), or by pre −/ post- periods of construction of dams (Kesel, 1989). These subdivision methods were verified to improve estimation results of *SSC* and *SSL* in many large rivers around the world, such as the Amazon River (Devol et al., 1986), the Mississippi River (Sivakumar and Chen, 2006), the Danube River (Mladenovic et al., 2013; Tóth and Bódis, 2015), the Rhine River (Asselman, 2000), the Nile River (Abdelazim et al., 2007), the Indus River (Ali and Boer, 2007), the Ganges River (Abbas and Subramanian, 1984), the Yangtze River (Xu et al., 2005) and the Yellow River (Shi, 2015).

The aims of this paper are to evaluate and improve SRCs for estimating *SSC* and, subsequently, *SSL* based on analysis of *Q* and *SSC* variability in the middle reach of the Yarlung Zangbo River over a period of three years. The purpose is to develop better SRC subdivision methods that are useful for water resource managers to evaluate *SSL*.

2. Material and methods

2.1. Study region

The Yarlung Zangbo River (hereafter YZR) (80°12′-97°38′E, 27°26′-28°54′N), originates from the Jiemayangzong Glacier at an elevation of 5590 m on the northern slope of the Himalayas, and flows from west to east across the southern part of the Tibetan Plateau (Fig. 1). The mean elevation of the basin is 4621 m a.s.l., ranging from 5590 m to several hundreds of meters a.s.l. The drainage area of the YZR basin is approximately 240,480 km^2, with an annual air temperature range of −0.3 to 8.8 °C for the time period 1960 to 2009 (National Meteorological Information Center, China, http://data.cma.cn/). Water discharge in the YZR basin is mainly recharged by precipitation, combined with glacier and snow melt water and ground water (Yao and Yao, 2010).

According to the topographic feature, valley shape, channel gradient, natural condition and runoff variety along the course of the YZR is divided into upstream, midstream and downstream by the Ministry of Water Resources of the People's Republic of China (MWR, PRC). Annual precipitation of the upstream, midstream and downstream of the YZR was < 300 mm, 300 to 600 mm and > 2000 mm, respectively. Detailed geographic features of each reach were listed in Fig. 1. The upper and lower reaches of the YZR basin exhibit hydrological differences due to the differences in climate, topography and land surface conditions (Liu et al., 2007; Wang et al., 2008).

According to the Genetic Soil Classification of China (GSCC), the soil order in the basin is mainly Alpine soil, which covers approximately 70% of the basin area (Zhang, 2011). The main soil types in the upper reach of the YZR basin are cold calcic soil and felty soil. The middle reach is dominated by felty soil, frigid soil and cold calcic soil, while felty soil, dark felty soil and dark brown soil persist in the lower reach. Soil texture in the basin is generally sandy loam (Zhang, 2011). Dominant vegetation of the three reaches is alpine meadow, alpine grass and alpine forest, respectively (Liu et al., 2012).

2.2. Data

There are three gauging stations located along the middle reach of the YZR, including the Lhaze, the Nugesha, and the Yangcun stations (Fig. 1). Basic information of the three gauging stations and the corresponding data are listed in Table 1. Daily discharge and SSC during 2007 to 2009 were recorded by the Lhaze, the Nugesha and the Yangcun gauging stations at three specific river cross sections along the YZR. According to the national standard “Code for liquid flow measurement in open channels” (GB 50179-93, 1993) issued by the MWR, PRC, daily discharge of a cross section was calculated by the weighted average of intraday instantaneous discharge obtained by water levels combining with specific stage-discharge relation curve. Water levels were measured every two hours during high flow period, every four hours during normal flow period and every twelve hours during low flow period by a self-recording water level gauge. The stage-discharge relation curve of a specific cross section was surveyed annually through cross section geometry, water level and flow velocity investigations during high, normal and low water flow periods. According to the national standard “Code for measurements of suspended sediment in open channels” (GB 50159-92, 1992) issued by the MWR, PRC, the instantaneous *SSC* sample was collected by a strip sampler at 60% of water depth and thereafter measured by oven drying method. Daily sediment load of the cross section was calculated by weighted average of instantaneous *SSC* and *Q*. The investigations of *SSC* were carried out while the variation of water level reaches 3% during high and normal water flow periods, and every 3–5 days during low flow period. Subsequently, *SSLs* were calculated by adding up products of paired daily discharge and *SSC* during specified time periods.

Since continuously or near-continuously discharge measurements in a river are much easier than high-frequency *SSC* measurements, accurate SRCs obtained under different flow regimes can be used to estimate *SSC* and *SSL* more frequently with discharge measurement data. It is important to ascertain whether or not the hydrological regime during the investigation period is representative, by comparing annual precipitation with the long term mean. Daily precipitation data were recorded at eleven meteorological stations within the study area (National Meteorological Information Center, China, http://data.cma.cn/). Station names and locations are depicted in Fig. 1. Precipitation data in the upstream of the three gauging stations were estimated by