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Spatio-temporal patterns of soil erosion and suspended sediment dynamics in the Mekong River Basin

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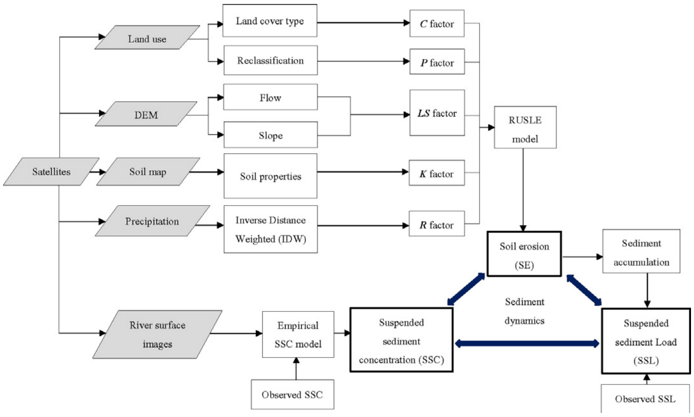
HIGHLIGHTS

- We proposed an integrated framework for sediment assessment at a basin scale.
- We estimate the spatio-temporal patterns of sediment dynamics in Mekong River Basin.
- We successful applied the framework in a large river basin in Southeast Asia.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding of the distribution patterns of sediment erosion, concentration and transport in river basins is critically important as sediment plays a major role in river basin hydrophysical and ecological processes. In this study, we proposed an integrated framework for the assessment of sediment dynamics, including soil erosion (SE), suspended sediment load (SSL) and suspended sediment concentration (SSC), and applied this framework to the Mekong River Basin. The Revised Universal Soil Loss Equation (RUSLE) model was adopted with a geographic information system to assess SE and was coupled with a sediment accumulation and a routing scheme to simulate SSL. This framework also analyzed Landsat imagery captured between 1987 and 2000 together with ground observations to interpolate spatio-temporal patterns of SSC. The simulated SSL results from 1987 to 2000 showed the relative root mean square error of 41% and coefficient of determination (R^2) of 0.89. The polynomial relationship of the near infrared exoatmospheric reflectance and the band 4 wavelength (760–900 nm) to the observed SSC at 9 sites demonstrated the good agreement (overall relative RMSE = 5.2%, $R^2 = 0.87$). The result found that the severe SE occurs in the upper (China and Lao PDR) and lower (western part of Vietnam) regions. The SSC in the rainy season (June–November) showed increasing and decreasing trends longitudinally in the upper (China and Lao PDR) and lower regions (Cambodia), respectively, while the longitudinal profile of SSL showed a fluctuating trend along the river in the early rainy season. Overall, the results described the unique spatio-temporal patterns of SE, SSL and SSC in the Mekong River Basin. Thus, the proposed

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integrated framework is useful for elucidating complex process of sediment generation and transport in the land and river systems of large river basins.

1. Introduction

Soil erosion and sediment dynamics in river basins are determined by a series of complex natural processes, which are strongly related to human activities such as deforestation, agriculture, urbanization and environmental management of basins and river corridors. Such activities often result in increased sediment loads causing many problems, for example a loss of reservoir storage capacity through sedimentation and increased turbidity in water distribution systems (Arnold et al., 1995). Soil erosion can be the major factor to increase the concentration of suspended sediment, which has been recognized as the most important contaminant affecting the Mekong water (Xue et al., 2011). In addition to its direct role in determining water turbidity, bridge scouring and reservoir storage, sediment serves as a carrier for the transport of many binding substances, including nutrients, trace metals, semi-volatile organic compounds and numerous pesticides (U.S. Environmental Protection Agency, EPA, 2000). Therefore, a reliable tool for monitoring and simulating soil erosion and suspended sediment patterns in basin scale is needed for basin development and management.

Soil erosion maps and its conservation planning have been widely developed on the basis of soil erosion models, which can be divided into two categories: empirical and physically-based models (Morgan, 1995). Empirical models are strictly based on the analysis of catchment data using stochastic techniques. The computational and data requirements for empirical models are usually fewer than those for physically-based models, and the output of empirical models is adequately supported by spatially coarse measurements. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), one such empirical model, is based on a large amount of data from the United States. The Agricultural Non-Point Source Pollution Model (Young et al., 1989) uses a revised form of the USLE. In contrast, physically-based models are based on fundamental physical equations describing stream flow and sediment generation in a river basin. These models have the potential to represent the physical processes observed in the real world, such as surface runoff, sub-surface flow, ground flow and evapotranspiration. Physically-based models are often used to describe the controlling processes of storm events. The Kinematic Runoff and Erosion model (Smith, 1981), the Water and Energy Simulations and Prediction model (Lopes and Lane, 1988) and the European Soil Erosion Model (Morgan et al., 1998) are examples of the physically-based erosion and sediment transport models. In addition, some models integrate both empirical and physically-based components such as the Soil and Water Assessment Tool (Arnold et al., 1998).

Meanwhile, the application of remote sensing in the assessment of inland water surfaces has recently escalated because of its capability of scanning wide water bodies within short time periods (Ritchie et al., 2003). Over the past three decades, remotely sensed images have been successfully used in the assessment of suspended sediment (Olmanson et al., 2008; Park and Latrubesse, 2014; Zhang et al., 2014; Du and Zhang, 2014). Remote sensing technology provides a potentially effective solution for monitoring suspended sediment in turbid rivers (Yang et al., 2011) because the effect of other optically active substances on the satellite data is negligible in such rivers (Lal, 2005). Consequently, a combination of erosion models with a spatial and temporal coverage afforded by remote sensing has the potential to provide a very useful tool for monitoring sediment dynamics and conducting effective basin management (Julian et al., 2008).

A number of studies have examined both water discharge and sediment behaviour in the Mekong River Basin (Delgado et al., 2009; Lu and Siew, 2006; Walling, 2008; Wang et al., 2001). Although many of these studies have recognized changes in water discharge and sediment load since the operation of dams began in the upper stream of the Mekong River (He et al., 2006; Kummu and Varis, 2007; Nguyen, 2003; Orr et al., 2012), no systematic analysis or variability estimation of the sediment dynamics (soil erosion, concentration and transport) has been conducted using a consistent framework. Thus, a systematic framework for the assessment of suspended sediment dynamics would significantly benefit the development of a decision support system. Moreover, such a framework can be a tool to assess and mitigate the effects of potential climate and land use changes on sediment dynamics processes, especially in areas with poor monitoring systems for sediment dynamics. Recently, spatial modelling using geographic information systems (GISs) have yielded progressively more suitable tools for the fields of research, such as forestry, agriculture, hydrogeology and soil science (Bocchi et al., 2000; Lu et al., 2004; Chen et al., 2011a, b; Chen et al., 2014), as this technique can analyzes spatially distributed data and thus its useful for understand sediment dynamics.

The aim of this study is to propose an integrated framework for sediment assessment at a basin scale and to apply the framework to estimate the spatio-temporal patterns of sediment dynamics in the Mekong River Basin. We assessed the basin-scale distribution of SSL by coupling the Revised Universal Soil Loss Equation (RUSLE) with a simple scheme for sediment accumulation and routing. Within the framework, we also employed satellite images for monitoring SSC and estimating its spatio-temporal profile. The proposed framework can be also applied to basins for which there are a limited set of observations (e.g. river discharge) because the proposed framework does not require a hydrological model to the assess sediment dynamic processes.

2. Target river basin

The target of this study is the Mekong River Basin, which is the largest trans-boundary river basin in Asia. The Mekong River originates in Tibet, China, and it flows southward to Southern Vietnam, a distance of more than 4600 km. The Mekong River Basin covers an area of approximately 795,000 km^2 (Fig. 1) (MRC, 2005) and delivers 475 km^3 of fresh water per year and approximately 160 million tonnes of sediment per year into the South China Sea (Milliman and Meade, 1983). Compared to other major rivers in Asia, the Mekong ranks eighth with respect to average annual runoff (Pantulu, 1986) and is the third largest river in terms of sediment load (Darby et al., 2013). The climate of the lower Mekong (from the China border to the south) is humid and tropical. Mean annual rainfall ranges from 1000 mm in the Thai part to 3200 mm in the mountainous region of Lao PDR (Kite, 2001).

Currently, the Mekong River Basin is experiencing rapid population and economic growth. Increasing demands for hydropower and fresh water has resulted in the construction of a growing number of dams and reservoirs along the river mainstream. For example, the controversial hydropower project on the Mekong River is the Lancang Cascade within China's Yunnan Province in the upstream area. Since the completion of the Manwan Dam in 1993, there has been an ongoing debate about its positive and negative impacts on the Lower Mekong River Basin (Nguyen, 2003). The general consensus is that although there was a sharp decrease in sediment flux at Chiang Sean shortly after completion of the dam, downstream stations did not experience abrupt changes (Lu and Siew, 2006; Kummu and Varis, 2007).

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