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A semi-physical sediment yield model for estimation of suspended sediment in loess region

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ABSTRACT

Sediment yield is a complex function of many environmental factors including climate, hydrology, vegetation, basin topography, soil types, and land cover. We present a new semi-physical watershed sediment yield model for the estimation of suspended sediment in loess region. This model is composed by three modules in slope, gully, and stream phases. For slope sediment yield, a balance equation is established based on the concept of hydraulic erosion capacity and soil erosion resistance capacity. According to the statistical analysis of watershed characteristics, we use an exponential curve to approximately describe the spatial variability of watershed soil erosion resistance capacity. In gully phase, the relationship between gully sediment concentration and flow velocity is established based on the Bagnold' stream power function. In the stream phase, we assume a linear dependence of the sediment volume in the reach on the weighted sediment input and output. The proposed sediment yield model is operated in conjunction with a conceptual hydrologic model, and is tested over 16 regions including testing grounds, and small, medium and large watersheds in the loess plateau region in the mid-reach of Yellow River. Our results indicate that the model is reasonable in structure and is able to provide a good simulation of sediment generation and transportation processes at both flood event scale and inter-annual time scale. The proposed model is generally applicable to the watersheds with soil texture similar to that of the loess plateau region in the Yellow River basin in China.

1. Introduction

Information of erosion and sediment yield in a changing environment and its effects on sedimentation in reservoirs, channels, and harbors are increasingly sought by catchment stakeholders and managers (Boix-Fayos et al., 2008; Kunze & Stednick, 2006; White, 2005; Wilson et al., 2001). This information is required at spatial and temporal scales that reflect the processes of erosion, transportation, and deposition in response to rainfall events, runoff, and etc. Various models are developed to simulate these processes (Francke et al., 2008; Kisi et al., 2006; Merritt et al., 2003; Mishra et al., 2007; Xu et al., 2009). These models fall into three main categories including empirical or statistical, conceptual, and physics based models based on the different ways of simulating physical processes, the algorithms describing these processes, and their data dependence (Merritt et al., 2003). Empirical models are based primarily on the analysis of observations or professional experiences such as the basic Universal Soil Loss Equation developed in the 1970s by United States Department of Agriculture (Hudson, 1993) and Soil Loss Estimation Model for Southern Africa (Elwell, 1978). These models depend on a database from experimental plots, which limit their application to other regions without enough experimental plots (Boomer et al., 2008; Sommerlot et al., 2013). Physics-based models, on the other hand, are based on the solution of fundamental physical equations describing streamflow and sediment movement such as equations of conservation of mass and momentum for flow and sediment. These models, such as Limburg Soil Erosion Model (De Roo & Jetten, 1999), the Watershed Erosion Prediction Project (Laflen et al., 1991), and the Distributed Runoff and Erosion Assessment Model (Ramsankaran et al., 2013), are restricted to study watersheds where there has been considerable work undertaken for the description of the watershed and necessary inputs. Empirical

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models and physics-based models are identified as two extreme model types going from considerably simplified processes with unrealistic assumptions about the physics of the watershed system to highly detailed representations of the processes that require huge amount of time to develop and implement them for a specific region (Merritt et al., 2003). As a result, developing a semi-physical model with reasonable structure and high computation efficiency on either a continuous basis or in an event-based mode is needed.

Most of current conceptual sediment yield models focus on sediment movement either in upland phase such as rill and gully erosion or lowland stream phase (Bennett, 1974; Bhunya et al., 2010; Wang, et al., 2007). Few of them have been developed for watershed sediment generation (Aksoy & Kavvas, 2005). Watershed sediment generation is a complex function of many environment factors including climate, hydrology, vegetation, basin topography, soil types, and land cover (De Vente et al., 2006; Van Rompaey et al., 2002; Van Rompaey et al., 2001). Previous studies have strived to explore the relationship between soil erosion and each of these factors (Boomer et al., 2008; DiBiase & Lamb, 2013; Guo, et al., 2012; Hassan, et al., 2008; Simoes, 2014). A full consideration of these factors usually results in either a complex conceptual model or a physics-based model for which the required inputs can seldom be satisfied. A comprehensive review by Merritt et al. (2003) indicates that a development of models that are capable of simulating on an event basis, yet minimize the process representation to only those key processes that control watershed response, is an on-going research area. For this purpose, we categorize the various factors into time-varying and time-invariant factors based on the simulation period. The model structure can be simplified to reflect the key processes by considering the time-varying factors in model structure while reflecting the time-invariant factors by parameters (Bao, 1994, 1995, 1997; Bao & Wang, 1995).

Here we propose a semi-physical model for suspend sediment yield in loess region. By the definition of hydraulic erosion capacity and soil erosion resistance capacity, and the development of spatial distribution curve of soil erosion resistance capacity, we are able to create a semi-physical framework of event responsive watershed sediment generation structure. We also illustrate the conceptual structure of sediment movement in gully and stream phase (Section 2). The proposed sediment yield model is coupled with a conceptual hydrologic model and is tested over 16 regions including testing grounds, the small, medium and large sized watersheds in the loess region in the middle reach of Yellow River (Section 3). We then discuss the main factors responsible for the model performance and accuracy, and the implications for interpreting the observations of sediment yield at different scales.

2. Model structure

2.1. Slope sediment generation mechanism

Sediment generation on a slope is accomplished by four different processes according to their dynamic influences on the suspended sediment yield at the watershed outlet. These are before-storm soil erosion, erosion by raindrop splash, transport by runoff, and detachment and deposition along the flow path. Before-storm and raindrop splash soil erosions are important in sediment yield calculation as they provide the original sources for sediment transportation (Alekseevskiy et al., 2008; Dragoun, 1962; Salles et al., 2000). Changes in precipitation including precipitation extremes (Shi et al., 2015) and precipitation storm properties (Jiang et al., 2013a, 2013b; Yu et al., 2015) will impact on the soil erosions. However, they act indirectly on the suspended sediment yield at the watershed outlet. That is, they will not contribute to the sediment yield unless transported by runoff. Before-storm and raindrop splash soil erosions are considered insensitive on the sediment yield in loess regions where these two processes usually provide enough loose soil for the transport process at most locations. As a result, we reflect them by the parameters rather than consider them in the model structure. Sediment transport by runoff is mainly controlled by hydraulic factors, which is easy to be conceptualized into model structure. Detachment and deposition along the flow path are determined by both hydraulic erosion capacity and soil erosion resistance capacity which has a complex mechanism and is difficult to be conceptualized. To solve this problem, we define the concept of the hydraulic erosion capacity which is controlled by the time-varying hydraulic factors and the soil erosion resistance capacity which is determined by time-invariant soil characteristics, and consider them separately in our model development.

2.1.1. Mass balance in slope sediment generation

The particle detachment is controlled by the locally intense shear stresses (τ) generated at the soil surface and the cohesive strength of the soil sediment. The detachment occurs when the shear stress exceeds the cohesive strength (Fig. 1). The slope sediment generation can be estimated based on the spatial distribution of particle diameter and forces acting on the particle which, at current time, is not accessible due to the insufficient time or funds. In this situation, more conceptual description is more appropriate. As a result, we propose the concepts of hydraulic erosion capacity and soil erosion resistance capacity and investigate the quantitative relationships between them. We define the hydraulic erosion capacity as the total amount of sediment that overland flow can carry when the supply of sediment exceeds the flow's transport capacity. The hydraulic erosion capacity is only controlled by hydraulic factors as described below:

$$S_c = T_c \cdot H \cdot A \tag{1}$$

where S_c is the hydraulic erosion capacity of the slope flow (kg); T_c is the transport capacity (kg/m^3); H is the depth of the surface runoff (m); A is the area of the slope surface (m^2). However, the actual sediment load is limited and is usually less than the hydraulic erosion capacity when the availability of sediment stands below the flow's transport capacity. In these cases, detachment occurs. During detachment processes, cohesive strength between sediment particles is another factor which contributes to the difference between actual sediment yield and the hydraulic erosion capacity. Generally, the larger cohesive strength between sediment particles caused the less actual sediment yield. Here, we define the soil erosion resistance capacity as the difference between actual sediment yield and the hydraulic erosion capacity. The upland sediment production balance can be

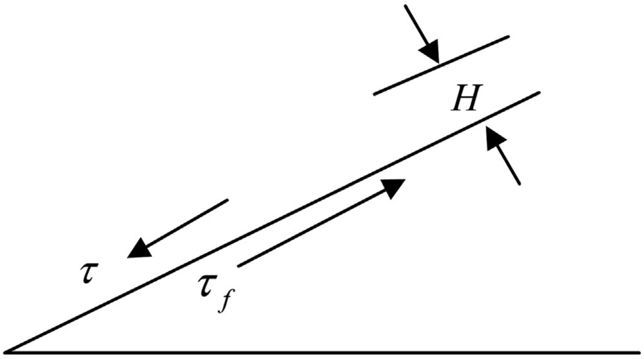

Fig. 1. Forces acted on soil particle. *H* is the depth of the surface runoff.

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