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Time-varying sensitivity analysis of hydrologic and sediment parameters at multiple timescales: Implications for conservation practices

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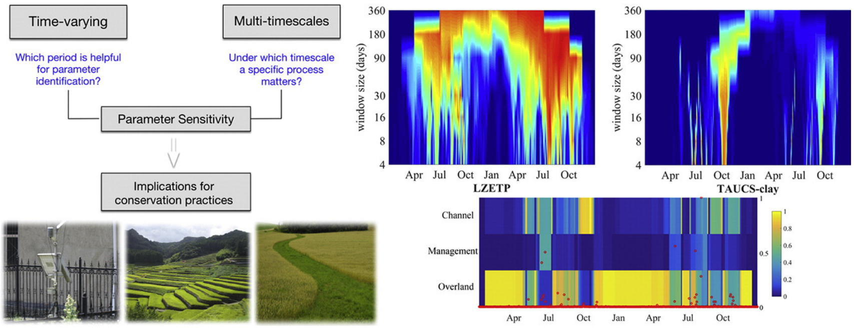
HIGHLIGHTS

- Parameter sensitivity varies notably depending on catchment conditions.
- Evaluation scales affect the distribution of parameter sensitivity.
- Combined consideration improves the understanding of watershed processes.
- Selection of BMPs for sediment control should be storm-dependent.

GRAPHICAL ABSTRACT



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ABSTRACT

Environmental models can be used to better understand the hydrologic and sediment behavior in a watershed system. However, different processes may dominate at different time periods and timescales, which highly complicate the model interpretation. The related parameter uncertainty may be significant and needs to be addressed to avoid bias in the watershed management. In this study, we used the time-varying and multi-timescale (TVMT) method to characterize the temporal dynamics of parameter sensitivity at different timescales in hydrologic and sediment modeling. As a case study, the first order sensitivity indices were estimated with the Fourier amplitude sensitivity test (FAST) method for the Hydrological Simulation Program - Fortran (HSPF) model in the Zhangjiachong catchment in the Three Gorge Reservoir Region (TGRR) in China. The results were compared to those of the traditional aggregate method to demonstrate the merits of the TVMT method. The time-varying nature of the hydrologic and sediment parameters was revealed and explained mainly by the variation of hydro-climatic conditions. The baseflow recession parameter, evapotranspiration (ET) parameter for the soil storage, and sediment washoff parameter showed high sensitivities almost across the whole period. However, parameters related to canopy interception and channel sediment scour varied notably over time due to changes in the climate forcing. The timescale-dependent characteristics was observed and was most evident for the baseflow recession parameter and ET parameter. At last, the parameters affecting the sediment export and transport were discussed together with the inferred conservation practices. Reasonable controls for sediment must be storm-dependent. Compared to management practices on the land surface, practices affecting channel process would be more effective during storm events. Our results present one of the first investigations for sediment modeling in terms of the importance of parameter sensitivity in both time periods and evaluation timescales for the model calibration, diagnostic evaluation, and prioritizing efforts for conservation practices.

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1. Introduction

Intensive rainfall and anthropogenic activities cause severe flood and soil erosion in agricultural watersheds with steep slopes, such as in the mountainous areas of the Three Gorge Reservoir Region (TGRR) in China. Nutrients and anthropogenic pollutants may then be absorbed and be transported by suspended sediments from upland areas. This represents a major threat to the aquatic system (Dong et al., 2015; Hostache et al., 2014). Conservation practices are believed to reduce and delay excessive runoff and soil erosion. Terraces, strip cropping, and terraces are widely implemented in watersheds (Xie et al., 2015). The hydrology and sediment dynamics depend on several variables including local topography, soil characteristics, climate, vegetation types, land use, and channel geometry. Thus, the related processes are generally very complex and highly nonlinear. They vary spatial-temporally; hence, the monitoring of the discharge, sediment yield, and transport become challenging (Sánchez-Canales et al., 2015). Modeling is an alternative to estimate and understand the watershed processes and is thus of critical importance for the development of watershed management plans, such as the total maximum daily loads (TMDLs) in the United States and the Water Framework Directive in the European Union (Ahmadi et al., 2014; Liang et al., 2016).

Despite of structure errors, environmental models may still not be able to accurately characterize all physical processes because a large number of parameters are often difficult to measure and therefore need to be calibrated (Shen et al., 2014). The uncertainties of these parameters may therefore be significant and need to be addressed to improve the model interpretation and to avoid bias in the watershed management especially with designing effective mitigation measures involved (Chavas, 2000; Liu et al., 2008). Sensitivity analysis (SA) is a diagnostic approach widely used for exploring uncertainty within complex parameter spaces and interpreting model behavior. In watershed modeling, SA usually serves for the assessment of contributions of individual uncertain inputs/parameters to the uncertainty in the model outputs. The sensitive parameters identified provide guidance for decision makers to address dominant control processes that will be targeted for the implementation of practices (Ferretti et al., 2016). The traditional application of SA is based on aggregation of model residuals across the whole time series, which leads to a constant parameter sensitivity. However, due to the temporal variation of the watershed processes, the parameter sensitivity may be time-variant. A time-varying analysis is an improvement and can help to diagnose to what extent the parameters can impact the model outputs in different time periods. Therefore, the dominant processes and conditions for the derivation of a more reasonable management plan could be identified (Ghasemizade et al., 2017; Pianosi and Wagener, 2016).

The moving window approach is a method commonly used to characterize the temporal dynamics of parameter sensitivity. The evaluation in windows is less susceptible to outliers in the data and, more importantly, it allows for the parameter identification as a function of time (Wagener et al., 2003). In hydrologic modeling, time-varying analysis using the moving window approach has been suggested for environmental models over the last decades. Herman et al. (2013) used a high-resolution moving window with a 24 h length to details the time-varying nature of sensitivities of hydrologic parameters. A moving window of 15 days before the specific day is used by Guse et al. (2014) to investigate the temporal dynamics of model performance. Pianosi and Wagener (2016) applied a temporal analysis on 31-day windows to address uncertainties with hydrologic modeling. However, the window sizes were fixed in most of this research, which indicates that the sensitivity analysis was performed for only one evaluation timescale. Because different processes act at different timescales, an analysis across the timescales is needed to ensure that no information is lost. Wagener et al. (2003) studied the effects of timescales on dynamic identifiability analysis for the first time. Massmann et al. (2014) proposed a time-varying and multi-timescale (TVMT) method which incorporated 14 degrees of window sizes to fully capture the effect of evaluation timescales. The results were used in the model calibration and diagnostic evaluation of the realism of the model structure. The advantages of using the TVMS method have not been confirmed in the sediment modeling, because to our knowledge, no studies have been carried out. However, in practice, the high risks posed by excessive suspended sediment instreams are particularly evident and receive much attention from practitioners and policy makers.

In this study, we use the TVMT method to address two questions: 1) Can we understand the sensitivity of not only hydrologic parameters, but also sediment parameter across both time periods and timescales? and 2) How can we get the most out of the sensitivity results for measurement campaigns and implementation for conservation practices? As an environmental model for hydrology and sediment dynamics, the Hydrological Simulation Program - Fortran (HSPF) model was selected for this study because it contains typical structural components (Bicknell et al., 1997). We applied our analysis to the Zhangjiachong catchment, which is a typical small catchment located at the top of the TGRR in China, characterized by soil erosion and water quality degradation. Our results present one of the first investigations for sediment modeling in terms of the importance of parameter sensitivity in both time periods and evaluation timescales.

2. Methods and materials

2.1. Catchment description and data collection

The Zhangjiachong catchment is approximately 162 ha in size and is located in the southwestern Zigui County, which is in the top of the TGRR. It is a sub-watershed of the Moping River, which drains directly into the Yangzi River. The topography is predominately hilly, with an elevation between 148 m and 530 m above the Yellow Sea level. The lower terrain of the catchment slopes gently, whereas the upper–middle part has a steep topography. The catchment is primarily agricultural land planted with tea, corn, cole and chestnut. Forest also covers 43% of the area, whereas urban land only comprises 1%. The catchment has yellow-brown soil, which is classified as Alfisol in the China Soil Scientific Database. The mean annual air temperature is 18 °C and the annual precipitation averages to 1439 mm, approximately 80% of which occurs from May to October. Storms are very common in the wet season and cause severe soil erosion. The total area of soil erosion resulted from the storms has reached even 60% of the catchment area in 2001. Fig. 1 shows the location and stream network of the catchment.

The development of a HSPF model requires spatial data, meteorological data, and monitoring data for calibration and validation. The field experiments from January 1, 2011 to December 31, 2012, of this study included weather measurements, discharge and sediment measurements, topographic analysis, and land use surveys. A weather station (SkyeLynx Standard) located at the watershed outlet provided a continuous record of climate data (e.g., rainfall, temperature, and wind speed) required by the HSPF model. A water level sensor (WGZ-1) was also located at the watershed outlet and a data logger took daily readings. The spillway was rectangular-shaped; hence, the discharge could be well estimated. The sampling strategy was designed to characterize the suspended sediment concentration (SSC), which was only monitored on storm-event days in the two years. These data were centralized in May to September, and could well capture the trend and reflect how the Zhangjiachong catchment would respond to major rainfall events. The reason why there was no measurement in non-storm periods is that, in the Zhangjiachong catchment, the water level is scarcely increased during events with rainfall amount lower than 25 mm. At this time, the SSCs could be lower than 0.001 g/L in the dry season from the test experience of local technical staffs. Compared to our monitored SSCs, these values are rather small. Based on these facts, the two-year monitoring collected 24 SSCs for 24 major event days. The contour map, land use map, and soil maps were all created based on field