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Estimating long-term sediment export using a seasonal rainfall-dependent hydrological model in the Glonn River basin, Germany

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ABSTRACT

In European catchments, rainfall and overland flow trigger erosive processes that could result in soil detachment and transportation. However, estimation of both erosive rainfalls and sediment yields is very challenging, especially in historical times when only precipitations at seasonal or annual scales are available. This motivated us to develop a parsimonious hydroclimatological model (ASCLIM, Annual Sediment CLImatological Model) for predicting catchment scale sediment yield when temporal and spatial high-resolution precipitation data are not available. The model was developed by using the annual data of suspended-sediment yield from Glonn basin (1981–1995, gauge of Hohenkammer, Germany) and seasonal rainfall data from a NOAA data set. The correlation coefficient between predicted and observed sediment yields was 0.94 and the efficiency index was 0.89. Once parameterized, the model was able to capture annual sediment yield variability better than the Langbein–Schumm and the Fournier Index equations, also based on limited sets of inputs. The model holds potential for historical reconstruction of sediment yields in the Glonn catchment (assuming constant land cover) and for simulating sediment fluxes from catchments with similar characteristics. Our application highlights the control of rainfall seasonality on sediment export and demonstrates that our sediment yield proxy could be considered as a good tool for the expectation and planning of soil conservation. Moreover, considering that we used modeled data to reconstruct past sediment loss, we could expect that using projected future rainfall data our proxy could be able to assess future scenarios.

1. Introduction

Assessing effects of climate change on hydrology has been an important area of research in recent decades, in particular with respect to land degradation (Morán-Tejeda et al., 2010; Ravi et al., 2010; Liu et al., 2014). Research on erosional soil degradation requires understanding of spatial and temporal changes in rainstorm patterns, which may affect the variability of total sediment loads (Gao et al., 2011). Sediment yield is a measure of the sediment exported over a given time and a space unit, as produced by all erosional sources — including splash erosion, rill and interrill, ephemeral gully and stream channel erosion, and mass movements (de Vente and Poesen, 2005). At a global scale, estimates of the seasonal flux of sediment were documented by Syvitski et al. (2005) using a simple regression model based on only a few parameters. Sedimentation rate is affected by climate, vegetation cover, land use, soil erodibility, and slope gradients (Toy et al., 2002). Soil erosion, sediment transport, and deposition have been well described (Morgan, 1986; Rose, 1993; Haan et al., 1994; Boardman and Poesen, 2006), and methods have been designed for monitoring of suspended sediment yield and bedload at different spatial and temporal scales (Pavanelli and Pagliarani, 2002; Bunte et al., 2004; Gao, 2008).

The relationship between sediment yield and precipitation has been receiving attention since the pioneer work by Langbein and Schumm (1958), who suggested that the available energy for erosion and transport increases positively with the amount of effective annual rainfall up to about 300 mm. At higher annual rainfall amounts, perennial and annual vegetation cover increases surface protection and limits soil erosion and sediment yield. The importance of precipitation seasonality was highlighted by Oliver (1980), Kirkby and Neale (1987), and Michiels et al. (1992). They concluded that concentration of precipitation in high intensity events leads to higher annual erosion rates. For

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instance, if high intensity rain is concentrated in seasons with low vegetation cover (before crops are on the field or just after harvest), then their effect will be stronger. However, the opposing influence of precipitation components (e.g., decreases in annual amount and increases in seasonal concentration) can result in a complex spatial pattern of runoff-and-erosive rainfall and erosion processes (De Luis et al., 2010).

Runoff and rainfall erosivity are controlled by the extremes of precipitation and may occur in some stormy years or months according to the rain regime of D'Odorico et al. (2001). Identification of interdecadal rainfall variations may help predict the possible consequences of abrupt environmental changes over long time periods (Diodato et al., 2008). It also provides a new perspective to the study of landscape conservation and climate change, especially in highly dynamic systems (such as agricultural river systems), controlled by complex climatic, geomorphic, and ecological processes (Krishnaswamy et al., 2000).

A wide range of soil erosion and sediment yield prediction models were developed over the last decades, but they vary enormously in level of complexity (Jetten et al., 2003; Merrit et al., 2003; de Vente and Poesen, 2005). In general, more complex models are mostly applied to relatively small catchments and short time periods because of their high input data requirements and calibration difficulties (de Vente et al., 2009). Examples of erosion modeling at longer time scales were presented by Macklin and Lewin (2003), Zolitschka (2003), Dotterweich (2008), Notebaert et al. (2009), and Ward et al. (2009). In these cases, efforts were directed toward reducing the complexity of models to a few key inputs in order to capture interannual and multidecadal variability (after Diodato et al., 2014). Many of these models have not been able to reflect in much detail the potential effect of changes in the hydroclimatological force driving erosion and sediment yield. Moreover, the possibility to describe the temporal rainstorm pattern at catchment scale is complicated by factors such as local climatic conditions, the localized nature of the rain events, and inconsistency in spatial and temporal data resolution.

Long-term records of runoff and sediment yield are scarce, which makes the control of precipitation patterns on soil degradation very challenging (Taguas et al., 2013). The access to long records of subdaily input rainfall data for modeling is also critical because data of this type are only available for a few, geographically scattered stations (Diodato and Bellocchi, 2010). Given this lack of data, interest is high in developing parsimonious approaches to model erosion and sediment yield with low data requirements and with the potential to be applied in small-to-medium sized, unmonitored basins. This is especially true where these basins are recognized as the most vulnerable to rainstorm-driven floods and sediment yield (Ruin et al., 2008). In small catchments, relatively few high magnitude events are responsible for the main part of the sediment export (Gonzalez-Hidalgo et al., 2013), and high-intensity rainfall events are often held responsible for the main part of soil erosion (Baartman et al., 2012). It is also known that the hydrological response after high-intensity, low-frequency storms is independent on the initial soil water content (Castillo et al., 2003). Thus, although it is not possible to directly relate the single heavy rainfall events to soil erosion types and sediment yields, the knowledge of the frequency and distribution of seasonal rains can help to define potential predictors for the purpose of modeling annual sediment yield. A possibility to overcome the lack of detailed inputs is to consider sediment yield as a temporal phenomenon that reflects magnitude and frequency of individual storm events nested within the seasonal regime patterns. In this study, we developed a new low complexity proxy of sediment yield, the ASCLIM (Annual Sediment CLImatological Model) by incorporating seasonal precipitation input variables only. Although this model was developed on the basis of the same data of Krysanova et al. (2002), improved results and model complexity reduction underline the need of this study. The ASCLIM was calibrated and applied to the Glonn River basin (GRB) in Germany in order to reconstruct sediment export over the last three centuries. The landscape of this catchment is dominated by arable cropland (Krysanova et al., 2002), with regular cultivation patterns and relatively homogeneous soil types and topography. These features make the GRB an interesting case for evaluating simplified approaches to model annual sediment yields and explore the role of seasonal rainfall distribution as the main driver of soil erosion and sediment transport over historical times, for which only low-resolution precipitation data are available.

The model was applied to the reconstruction of a continuous series of annual sediment yields in the GRB. Additionally, in order to further evaluate the ASCLIM and underline its ability under different geographic and climatic conditions, the model was tested using historical data from the Füssen–Lech basin (FLB).

2. Environmental setting

The study area is the Glonn River basin. Stream discharge and suspended sediment yield data were from the Hohenkammer station (48°25′ N., 11° 32′ E.). The Glonn River basin is part of the upper Danube basin (Bavaria, Germany) and has an area of 392 km^2 (Fig. 1). The Glonn River is a major tributary of Amper, which is a tributary of the Iaar River.

Basin elevation ranges from 450 to 559 m above sea level (asl.) and loamy loess soils dominate in the basin area (about 60%). The rest of the soils of the basin are mainly sandy to sandy-loess (about 33%) with limited percentages of clay-type and peat soils. The area is dominated by arable cropland (73%), while forest occupies 16.5% of the drainage area and the rest is grassland (Krysanova et al., 2002).

The Glonn River basin is located within a high flood occurrence area of Europe (Fig. 1a).

In this region, the most extreme storm events are induced by instabilities produced by the frontal air masses brought from the North Atlantic, which result in summer and in early autumn precipitation maxima (Heino et al., 1999). These circulation patterns can be associated with prolonged rainfall-driven large floods and sediment yield and with intensive rainstorm-driven, flash and intermediate floods with accelerated soil erosion (Diodato, 2006). Large floods may be accompanied by continuous runoff with high sediment transport capacity. Climate in this basin is typical of subcontinental central Europe. The yearly and seasonal distribution of precipitation over the area is the result of synoptic circulation that advects air masses of different origins (arctic, polar maritime, and polar continental). These air masses allow high storage of humidity that represents the main energy supply for thunderstorms, which are triggered by outbreaks of Atlantic polar maritime air in the mid-troposphere. The thunderstorm season usually extends from the end of May to mid-October. Average annual precipitation is about 880 mm y^{-1}, and the long-term (20–30 years) catchment-scale runoff coefficient (fraction of precipitation that appears as runoff) is 0.30 (Krysanova et al., 2002).

The additional training and validation area is the Fussen-Lech basin, which has been described in detail by Diodato et al. (2014). This basin is in the mountainous range of the upper Danube basin and the annual average precipitation is 1525 mm (data from Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region, HISTALP, http://www.zamg.ac.at/histalp; Efthymiadis et al., 2006). According to our data, the long-term average suspended-solid yield is 235 Mg km^{-2} y^{-1}, with distinct variability (interquartile range = 137 Mg km^{-2} y^{-1}). Land use is dominated by forests and alpine meadows (>60%), while arable land is sparse. Although the unfavorable environmental setting caused the decline of the agricultural sector during the last decades (Lantschner-Wolf, 1990), the overall land cover did not change much since the nineteenth century (K.K. Statistische Central-Commission, 1864, 1883; Statistik Austria, 2011).

3. Model development and data

For this study, we have used the annual sediment export rates derived by daily water discharge and suspended sediment measurements available from 1981 to 1995 for the gauge station of Hohenkammer. Data were obtained from the Bayerisches Landesamt für Wasserwirtschaft