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Modelling spatially distributed soil losses and sediment yield in the upper Grande River Basin - Brazil

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A B S T R A C T

Water erosion negatively affects soil fertility, soil structure, and water availability to plants. Moreover, off-site erosion effects contribute to the sedimentation and eutrophication of water courses. The Grande River is one of the main tributaries of the Paraná River, and an important source of hydroelectric power in Brazil. The Upper Grande River Basin covers an area of 15,705 km^2, mostly occupied by rangelands. Shallow and little permeable Cambisols are the predominant soil class in the basin, which, combined with the intensive and highly concentrated summer rainfall, characterize an erosion-prone scenario. The aim of this study was to model the soil losses and the sediment yield in the Upper Grande River Basin. It also sought to quantify the sediment delivery to the two main hydroelectric power plant reservoirs in the basin: Camargos/Itutinga and Funil. Geographical Information Systems (GIS) were used to apply the Revised Universal Soil Loss Equation (RUSLE) and the Sediment Delivery Distributed model (SEDD) in the study area. The models were calibrated using sediment transport data obtained from a river gauging station located in a subwatershed. RUSLE predictions estimated that the average soil losses in the Upper Grande River Basin were of 22.35 t ha^{-1} yr^{-1}, and that bare soils, eucalypt and agriculture suffered the highest erosion rates among the identified land use classes. The average specific sediment yield in the basin was of 1.93 t ha^{-1} yr^{-1}. According to the model calibration, the specific sediment yield predictions showed an error of 0.01 t ha^{-1} yr^{-1}, or 0.6%. Agriculture and eucalypt forests, which compose approximately 10% of the study area, contribute to more than 40% of the sediment yield in the basin. The model predictions estimated that 1.45 million t yr^{-1} of sediments are delivered to the Camargos/Itutinga power plant reservoir, whereas the Funil power plant reservoir receives a sediment input of 1.68 million t yr^{-1}. Although model calibration yielded small errors in relation to the observed sediment measurements, the relative lack of available data has impaired a more thorough validation of the employed models. Nevertheless, the results indicate that the RUSLE/SEDD approach may be useful for analyzing sediment transport in Brazilian watersheds, where limited input data is available.

1. Introduction

Water erosion degrades soil structure, lowers soil organic matter and nutrient contents, thus reducing cultivable soil depth and depleting soil fertility (Dotterweich, 2013; Morgan, 2005). Erosion also decreases water absorption, which lowers soil moisture and water availability to plants (Pimentel, 2006) On-site soil erosion affects not only biomass, food and fiber production, but also diminishes farm income since it lowers cropland yields and increases the necessity of fertilizer applications (Poesen, 2011; Renschler and Harbor, 2002).

Off-site erosion impacts are also of great concern, especially sedimentation and eutrophication of water courses (Hu et al., 2009; Ouyang et al., 2010; Wu et al., 2012). As upland eroded sediments reach the stream network, river capacity reduces, and flood risk increases (Morgan, 2005). Sedimentation can also reduce the capacity of reservoirs, decreasing water storage and shortening the lifespan of hydroelectric power plants (Verstraeten et al., 2003).

Since direct erosion measurements are costly and time consuming, the development of soil erosion prediction models has received much attention from soil scientists. Early empirical erosion models were

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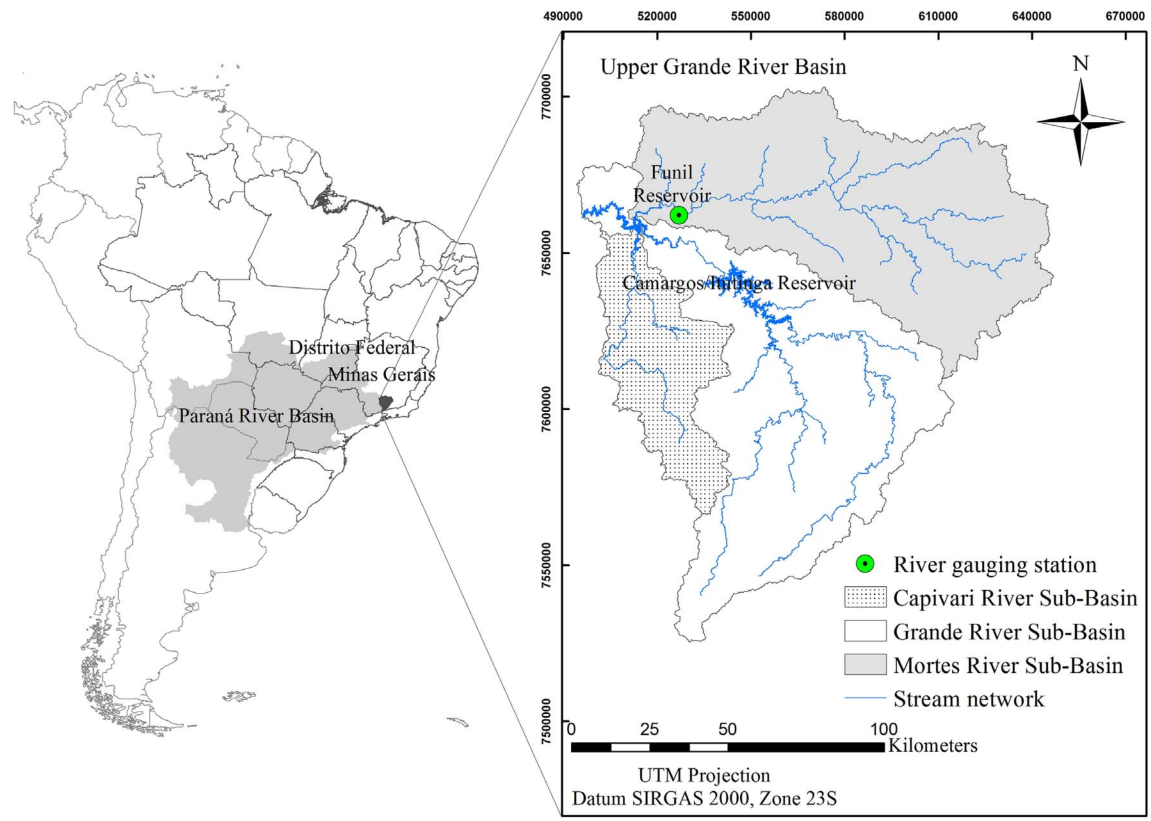

Fig. 1. Location of the Upper Grande River Basin.

developed in the USA during the 1940's and culminated with the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and its revised version (RUSLE) (Renard et al., 1997). USLE and RUSLE have been widely used, as their simple approach is useful where limited input data is available (Merritt et al., 2003; Renschler and Harbor, 2002). Although more sophisticated, process-based models are now accessible, RUSLE is still commonly employed, particularly at larger scales, through Geographic Information Systems (GIS) (Panagos et al., 2015b; Xiaoying et al., 2015; Xu et al., 2013). The combination of erosion prediction models with GIS has proved to be a powerful tool for evaluating soil losses at catchment scale, enabling the assessment of erosion rates in a distributed manner (Aksoy and Kavvas, 2005).

However, RUSLE only estimates gross erosion, providing no information on sediment delivery to water courses. Since only a fraction of upland eroded sediments reaches the catchment outlet, a sediment delivery ratio (SDR) is used to express the rate of gross erosion that eventually contributes to a river basin sediment yield (Walling, 1994). Sediment transport rates and patterns depend on many factors, such as catchment area, location of sediment sources, topographic characteristics, landscape connectivity, land use and soil texture (Vanmaercke et al., 2011; Walling, 1994). Therefore, a spatially distributed analysis of sediment production at watershed scale is critical in order to properly forecast off-site erosion impacts and to plan conservation strategies (Fernandez et al., 2003).

The Sediment Delivery Distributed (SEDD) model (Ferro and Minacapilli, 1995; Ferro and Porto, 2000) provides a semi-empirical and spatially distributed calculation of SDR. It is based on particle travel time from a given location to the nearest stream channel, following the hydraulic path of the overland flow. Ferro and Porto (2000) have suggested that during a long-period analysis, all sediments that reach the stream network are eventually discharged through the basin outlet. Therefore, the sediment delivery process could be simplified by neglecting channel deposition. The combination of RUSLE annual gross erosion predictions with SEDD by GIS processing provides an estimation of river basin sediment yield and a spatial identification of sediment sources. Such methodology has been applied in micro-catchments in Spain (Taguas et al., 2011) and Italy (Stefano and Ferro, 2007), as well as in large river basins in Turkey (Tanyaş et al., 2015) and China (Yang et al., 2012). To the authors' knowledge, however, the SEDD model has not yet been tested under tropical conditions, such as in Brazilian watersheds.

The State of Minas Gerais, Brazil, is strategically important to water resources in Brazil and South America. The state holds the springs of Grande, Parnaíba and São Francisco rivers. The first two are the main tributaries of the Paraná River, the second longest river in South America and the main source of hydroelectric power in the country. The Upper Grande River Basin is particularly relevant regarding hydroelectric power generation, since it supplies water to two important power plants: Camargos/Itutinga and Funil, which combined have a 280 MW generation capacity.

The Upper Grande River Basin received some of earliest settlements during the colonization of the State of Minas Gerais, thus suffering environmental impacts from mining and agriculture since the late 17th century. Reports of accelerated erosion and gully formation on the northern portion of the basin can be tracked to the 19th century (Burton, 1869). More recently, studies indicate a high erosion propensity within the Upper Grande River basin due to the erodibility of the soils and the absence of agricultural conservation practices (Beskow et al., 2009; Gomide et al., 2011). However, the relative lack of river gauging stations in the region hampers direct measurements of sediment concentration in the water, which highlights the importance of erosion and sediment delivery prediction models. Given the large size of Brazilian river basins and the coarse available data, erosion models must be able to provide useful information from a restricted database.

Hence, the aim of this study was to apply the RUSLE and SEDD models, using GIS, to predict the soil losses, sediment delivery rates, and sediment yield within the Upper Grande River basin, making it possible to identify the main sediment sources in the basin; and also, to