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Human impact on sediment fluxes within the Blue Nile and Atbara River basins

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ABSTRACT

A regional assessment of the spatial variability in sediment yields allows filling the gap between detailed, process-based understanding of erosion at field scale and empirical sediment flux models at global scale. In this paper, we focus on the intrabasin variability in sediment yield within the Blue Nile and Atbara basins as biophysical and anthropogenic factors are presumably acting together to accelerate soil erosion. The Blue Nile and Atbara River systems are characterized by an important spatial variability in sediment fluxes, with area-specific sediment yield (*SSY*) values ranging between 4 and 4935 t/km^2/y. Statistical analyses show that 41% of the observed variation in *SSY* can be explained by remote sensing proxy data of surface vegetation cover, rainfall intensity, mean annual temperature, and human impact. The comparison of a locally adapted regression model with global predictive sediment flux models indicates that global flux models such as the *ART* and *BQART* models are less suited to capture the spatial variability in area-specific sediment yields (*SSY*), but they are very efficient to predict absolute sediment yields (*SY*). We developed a modified version of the *BQART* model that estimates the human influence on sediment yield based on a high resolution composite measure of local human impact (human footprint index) instead of countrywide estimates of GNP/*capita*. Our modified version of the *BQART* is able to explain 80% of the observed variation in *SY* for the Blue Nile and Atbara basins and thereby performs only slightly less than locally adapted regression models.

1. Introduction

At global scale, a large spatial variability exists in the amount of sediment that is delivered to the oceans (e.g., Milliman and Meade, 1983; Ludwig and Probst, 1998). Even if estimates of present-day sediment fluxes are biased by a lack of data from tropical and mountainous catchments, most of the sediment clearly is produced in high relief, tectonically active terrains (Milliman and Syvitski, 1992; Hovius et al., 1997). Statistical analyses of sediment flux data revealed that the delivery of fluvial sediment to the coastal zone is largely conditioned by the area, river discharge, local topography, climate (air temperature), lithology, and human impact (Syvitski and Milliman, 2007). Walling and Webb (1996) estimated that about 50% of the global terrestrial flux is related to human activities. The exact magnitude of the human impact on the terrestrial sediment flux is still a subject of debate (Walling, 2009). Syvitski et al. (2005) have shown that human perturbations are accelerating soil erosion, while dam construction and water diversion are resulting in sediment trapping and reduced sediment fluxes to the coastal zone.

At the local scale (Fig. 1), a vast number of soil erosion studies exist that focus at the plot scale (e.g., Romero-Dìaz et al., 1999; Coppus and Imeson, 2002; Gyssels et al., 2005; Cerdan et al., 2010). Through detailed analyses of soil detachment and transport processes at experimental plots, they identified the main factors that are controlling soil erosion processes for different environments (Puigdefabregas et al., 1999). At the point scale, the detachment of particles through raindrop impact (splash) was found to be of critical importance (Le Bissonnais and Singer, 1992), whereas gully formation was more important at the hillslope or watershed scale (Fig. 1; Valentin et al., 2005). The impact of human activities on soil detachment and transport has long been recognized at the local scale (e.g., Lasanta et al., 2000; Molina et al., 2009). Various authors have pointed to the acceleration of soil erosion by human activities (Mwendera and Saleem, 1997; Molina et al., 2007; Vanacker et al., 2007).

The environmental factors controlling sediment flux are a function of spatial scale (e.g., Lane et al., 1997; Parsons et al., 2006; Syvitski and Kettner, 2008). Depending on the spatial scale under study, the dominant erosion processes vary because of different interaction levels between physical, chemical, and biological phenomena (Fig. 1; Renschler and Harbor, 2002; de Vente and Poesen, 2005). A regional assessment of sediment fluxes can fill the gap between the detailed, process-based understanding of erosion processes at the field scale and the empirical assessments of sediment fluxes at the continental or even global scale (Restrepo and Syvitski, 2006; Marston, 2010). The spatial variability in intrabasin sediment fluxes is particularly interesting as it can

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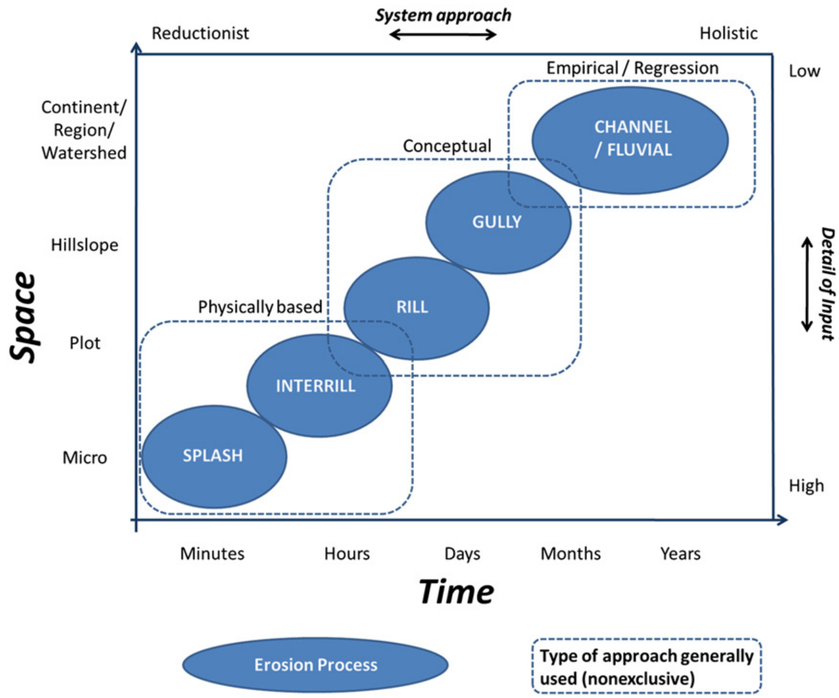

Fig. 1. Time–space plot showing different erosion processes and model types according to variations of scale (based on Renschler and Harbor, 2002; de Vente and Poesen, 2005).

provide new insights on the biophysical and anthropogenic factors controlling regional sediment fluxes (e.g., Verstraeten and Poesen, 2001; Vanacker et al., 2007; Nadal-Romero et al., 2011; Sougnez et al., 2011).

Importantly, understanding the effect of human perturbations on intrabasin sediment fluxes will be of crucial importance for future catchment management. Apart from the decrease in soil quality and productivity caused by accelerated soil erosion, human-induced changes in sediment fluxes are likely to have adverse ecological and environmental effects in a larger geographical area and may result in considerable financial and personal loss (Walling, 2009).

This paper examines the spatial variation in sediment fluxes in the Blue Nile and Atbara River basins and its response to biophysical and anthropogenic factors. The Blue Nile and Atbara regions are characterized by significant biophysical and anthropogenic constraints, which are presumably acting together to accelerate land degradation (Nyssen et al., 2004). Intense precipitation (qualified as highly erosive rains; Virgo and Munro, 1978) falling on intensively used soils for agricultural production are at the origin of major soil erosion problems (Nyssen et al., 2008; Tibebe and Bewket, 2011). Soil erosion increasingly deteriorates the chemical and physical soil properties to the point that a quarter of the land within the Ethiopian Highlands is considered to be severely degraded (Hadgu et al., 2009). It is estimated that in the absence of soil erosion control future agricultural production will stagnate and result in distressing food shortages, while rural incomes are expected to drop dramatically below the poverty line (Sonneveld and Keyzer, 2003).

The off-site effects of accelerated soil erosion are adversely affecting socioeconomic development of the downstream riparian regions of the Nile basin (Setegn et al., 2009; Betrie et al., 2011). The high sediment loads that are currently transported in the Atbara-Tekeze and Blue Nile River systems are leading to rapid siltation of reservoirs in Ethiopia, Sudan, and Egypt and are threatening existing and future water resource development in the Nile basin. To show the extent of the sedimentation problem, we give here some data for the Roseires reservoir based on data from Siyam (2010). The Roseires reservoir is located along the Blue Nile River in Sudan and is situated about 500 km south of Khartoum. It was constructed in 1966, with an initial capacity of 3329 million m^3 at a reduced level of 481 m. After 41 years of operation, the initial capacity was reduced by 42%. The average annual siltation rate during the period 1966–2007 was 34.34 million m^3. Partial blockage of the power intakes happens regularly during the flood season, and complete blockage occurred during the floods of 1975, 1983, and 2002.

By its regional approach, this study differs from previous studies that mainly focused on small agricultural catchments (Haregeweyn et al., 2008; Nyssen et al., 2008). Remote sensing data are used here as proxies of biophysical and anthropogenic site characteristics. The study has a double perspective, as it aims to analyze the spatial variation in erosion rates (or specific sediment yield) and total sediment yield within the Blue Nile and Atbara River basins. First, a robust statistical approach is used to determine the environmental factors that are controlling soil erosion at the regional scale. Regression techniques were then used to calibrate a numerical model that quantifies the spatial variability of specific sediment yield as a function of local biophysical and anthropogenic characteristics. Second, the outcome of this empirical, site-specific model is then compared to the application of a global sediment flux model, *BQART* (Syvitski and Milliman, 2007). The *BQART* model was originally developed to determine the 30-year normal of fluvial sediment flux to the coastal oceans and is tested here (in its original and modified versions) on its ability to estimate intrabasin variability in sediment yield at the scale of small- to medium-sized catchments (10^1–10^4 km^2).

2. Blue Nile and Atbara River systems

This study was conducted in the Blue Nile and Atbara River systems and encompasses the Blue Nile and Atbara River basins (Fig. 2). The Blue Nile basin drains a large portion of the central and southwestern Ethiopian Highlands, and it provides ~60% of the annual discharge of the main Nile in Egypt (Conway, 2000). The Atbara basin drains an area that is located in the northern part of Ethiopia and Eritrea. This river has its source 30 km north of Lake Tana and joins the main Nile 800 km downstream. Upstream of its confluence with the Tekeze River, the Atbara drains ~31,400 km^2