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Analyzing the variability of sediment yield: A case study from paired watersheds in the Upper Blue Nile basin, Ethiopia

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ABSTRACT

Improved knowledge of watershed-scale spatial and temporal variability of sediment yields (*SY*) is needed to design erosion control strategies, particularly in the most severely eroded areas. The present study was conducted to provide this knowledge for the humid tropical highlands of Ethiopia using the Akusity and Kasiry paired watersheds in the Guder portion of the Upper Blue Nile basin. Discharge and suspended sediment concentration data were monitored during the rainy season of 2014 and 2015 using automatic flow stage sensors, manual staff gauges and a depth-integrated sediment sampler. The *SY* was calculated using empirical discharge–sediment curves for different parts of each rainy season. The measured mean daily sediment concentration differed greatly between years and watersheds (0.51 g L^{-1} in 2014 and 0.92 g L^{-1} in 2015 for Kasiry, and 1.04 g L^{-1} in 2014 and 2.20 g L^{-1} in 2015 for Akusity). Sediment concentrations at both sites decreased as the rainy season progressed, regardless of the rainfall pattern, owing to depletion of the sediment supply and limited transport capacity of the flows caused by increased vegetation cover. Rainy season *SYs* for Kasiry were 7.6 t ha^{-1} in 2014 and 27.2 t ha^{-1} in 2015, while in Akusity *SYs* were 25.7 t ha^{-1} in 2014 and 71.2 t ha^{-1} in 2015. The much larger values in 2015 can be partly explained by increased rainfall and larger peak flow events. The magnitude and timing of peak flow events are major determinants of the amount and variability of *SYs*. Thus, site-specific assessment of such events is crucial to reveal *SY* dynamics of small watersheds in tropical highland environments.

1. Introduction

Soil erosion is a major global problem and is of particular concern in less-developed and drought-prone countries where subsistence farmers cannot replace lost soils and nutrients (Lal, 2001). In such nations, favorable agricultural and ecological conditions have drawn many people to settle in the highlands, leading to high population densities that sometimes exceed 300 people per km^2 and overexploitation of natural resources (Nyssen et al., 2009; Kassie et al., 2010; Haregeweyn et al., 2017). This is particularly true for the Ethiopian highlands, which experience a high rate of soil erosion as a result of intense rainfall in the steep and undulating topography, and the problem has been exacerbated by the use of agricultural systems that reduce the protective soil cover provided by native or natural vegetation (Nyssen et al., 2004).

In response to this problem, the Ethiopian government initiated a soil and water conservation (SWC) program since the 1970s, mainly in drought-prone areas (where drought increases soil vulnerability to erosion when rain does fall), and this was implemented on an ad hoc basis until it was replaced by a watershed-based approach in the 1980s (Haregeweyn et al., 2015). Over the years, the watershed-based approach has promoted various SWC measures, such as the creation of soil or stone bunds, *fanya juu* or bench terraces, cut-off drains, drainage canals, check dams, grass strips, and different shrub or tree plantations (Tefera and Sterk, 2010). Soil erosion, however, continues to be a problem, and SWC efforts targeted at wider geographic regions began

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with implementation of the Sustainable Land Management (SLM) Project in 2008.

Several plot scale studies have been conducted to evaluate soil erosion rates and the performance of some selected SWC measures on slopes in different parts of the Ethiopian highlands (Herweg and Ludi, 1999; Temesgen et al., 2012; Taye et al., 2013; Adimassu et al., 2014; Amare et al., 2014). These studies have monitored runoff and the sediment yield (*SY*) caused by sheet and rill erosion in small bounded runoff plots. Results from these studies have often been implicitly or explicitly extrapolated to watershed scales, which has been shown to produce misleading results (de Vente and Poesen, 2005) because of processes not captured by plot-scale measurements (e.g., gully erosion, bank erosion, mass wasting (Rijsdijk, 2005). Furthermore, the sediment supply in watersheds is heterogeneous in both time and space because it depends on the climate, land use, and landscape characteristics such as slope, topography, soil type, vegetation, and drainage conditions (Marttila and Kløve, 2010; Verbist et al., 2010). Therefore, watershed-scale estimates of *SY* and its spatial and temporal variation are needed for a variety of purposes, including the design of erosion-control structures (Russell et al., 2001) and evaluation of the effects of various land use and management practices (Gao et al., 2007; Sadeghi et al., 2008).

Improved site-specific knowledge of the variability of watershed-scale *SYs* are needed to design more effective erosion control strategies in Ethiopia's severely eroded areas, particularly in the humid tropical highlands of the Upper Blue Nile basin where high erosion rates exist owing to erosive rainfall, steep and undulating topography, and agricultural practices that reduce protective soil cover (Hurni et al., 2005). About 39% of the basin experiences severe or very severe erosion (Haregeweyn et al., 2017) that causes excessive sedimentation and threatens the sustainability of downstream reservoirs, including the Grand Ethiopian Renaissance Dam. Despite the magnitude of the problem, few assessments of watershed-scale spatial and temporal variability of *SY* exist in this basin, probably because of technical difficulties inherent in measuring the suspended sediment concentration (*SSC*) in discharge at sufficiently high temporal and spatial resolution (Verbist et al., 2010). Therefore, in the present study we monitored discharge and *SSCs* during two consecutive rainy seasons in paired watersheds located in the Upper Blue Nile basin. The main objective was to examine controls on spatial and temporal variations of discharge and *SY* in these two comparably-sized watersheds.

2. Study area

This study was conducted in two paired watersheds (Akusity and Kasiry) within the Guder subbasin of the Upper Blue Nile basin of Ethiopia (Fig. 1 and Table 1). The study site is located between 10° 57′ 23″N and 11° 11′ 21″ N and between 36° 40′ 01″E and 37° 05′ 21″ E, and is a typical representative of the biophysical conditions (i.e., vegetation cover, rainfall pattern, land use, and management practices) in the northwestern Ethiopian highlands. The elevation in the Guder area ranges from 2400 to >3000 m a.s.l., but the study site has elevations ranging between 2492 m a.s.l. at the outlet of the Kasiry River, and 2882 m a.s.l. at the highest point on the divide between the two watersheds.

The study area falls within the humid tropical climatic zone (Sultan et al., 2017), and corresponds to the *Dega* zone (i.e., cool, >2400 m above sea level) in the local climate classification system, characterized by a dry season that extends from November to April, and a wet season from May to October. Based on the 17 yr record (1999–2015) at the Injibara station (located about 5 km from the study area), the mean annual rainfall is 2454 mm (85% during the wet season), and the mean daily temperature ranges from 9.4–25 °C. Rainfall in 2014 (2635 mm) was above average and in 2015 (2239 mm) it was below average. Note that the higher annual rainfall in 2014 was caused by large rainfall amounts in February, March, and April (out of the sediment monitoring period of this study), whereas the contribution during these months was much smaller in 2015.

According to Mekonen (Amhara Design and Supervision Works Enterprise, Bahir Dar, Ethiopia, personal communication), the dominant soil types in the study area are Acrisols (equivalent to Ultisols in the USDA soil taxonomy), soils with subsurface accumulation of low-activity clays (i.e., highly weathered), low cation exchange capacity and low base saturation; Luvisols (i.e., Alfisols), very deep and well-drained soils that form on gentle slopes; Leptosols (i.e., Entisols), thin, degraded soils on steep slopes; and Vertisols, soils with a high content of clay minerals that shrink and swell during dry and wet seasons. The distribution of these soil types differ between the two studied watersheds. All four types occur in Kasiry, whereas only Leptosols and Luvisols exist in Akusity. The pH values for 18 samples collected from seven locations of the top 20 cm of Luvisols in the Kasiry watershed ranged from 5.35 to 5.90 (Kindye, 2016). This is within the range suitable for nutrient uptake and proper growth of most plants in the study area.

Farmers in these watersheds practice a mixed subsistence farming system based on crops and livestock. Major crops include tef (*Eragrostis tef*), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), and potato (*Solanum tuberosum*). Recently, small-scale farmers have adopted a *taungya* system using wattle trees (*Acacia decurrens*) that stabilize the soil during and after the growing season. These trees provide additional income from charcoal production, improve soil fertility, and provide soil and water conservation (Achamyeleh, 2015; Nigussie et al., 2017). Land managers anticipate that this change in land use will decrease erosion and *SY* over time (Bakker et al., 2008). In addition, physical SWC measures have been implemented by the SLM project for several decades to reduce the on-site and off-site effects of runoff and soil erosion. The most widely applied physical measures are the construction of soil bunds and trenches on hill slopes and drainage channels, without additional protective measures. Despite a considerable reduction in soil loss at the plot scale as a result of implementation of trenches and bunds (Kindye, 2016), absolute rates of erosion on steep cultivated slopes remain far greater than the tolerable limit (10 t ha^{-1} yr^{-1}) that has been suggested for Ethiopia (Taddese, 2001).

3. Materials and methods

3.1. Experimental setup

Gauging stations were installed at the outlets of the Akusity and Kasiry watersheds to monitor discharge and the *SY*. These stations were located in relatively stable and straight cross sections of the rivers to minimize sediment deposition in the channel (Yeshaneh et al., 2014). Each monitoring station was equipped with an automatic pressure transducer (TD-Diver; van Essen Instruments, Delft, the Netherlands), a staff gauge mounted at the side of the stream bed and strongly fixed in place with a concrete base, and a depth-integrated sediment sampler (Fig. 2). Flow stage, flow velocity, discharge, and the *SSC* were measured for 117 days during the wettest months (from 1 July to 25 October) in 2014 and 2015.

3.2. Streamflow and suspended sediment measurements

We measured discharge by monitoring stages automatically (10-min intervals) using the TD-Diver water level sensor, and manually three times per day (at 07:00, 13:00, and 18:00) using the graduated staff gauge (Fig. 2). The manual staff gauge was also monitored when peak flows or large changes in streamflow were observed. The relationship between the corresponding manual and automatic flow depth records was strong and significant ($R^2 = 0.87$ and $P < 0.001$ for Akusity; $R^2 = 0.81$ and $P < 0.001$ for Kasiry). We subsequently corrected the continuous automated flow readings using regression equations developed from