12. Sediment transport in the Geba River system

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1 Introduction

Soil erosion by water is one of the most important geomorphological processes in the Northern Ethiopian highlands. Studies on river discharge and sediment yield at the intermediate catchment scale (100 – 10 000 km^2) are however hardly available in the Ethiopian highlands. Nevertheless, huge investments are made for dam construction works in this region. Due to a lack of reliable river discharge and sediment yield data many dams and reservoirs have been over-dimensioned (Haregeweyn, et al., 2006). Likewise, many reservoirs fill up with sediments at an alarming rate because of the underestimation of sediment yield. This research, therefore, aims at a better understanding the river discharge and sediment yield dynamics in the Geba River system.

2 Study area

This study was conducted in the catchment of Geba River, a tributary of Tekeze (Atbara) and Nile River (Fig. 1). The Geba drains an area (A) of 5133 km^2 in the highlands of Tigray, northern Ethiopia. The Geba catchment is located between 38^{o}38'E and 39^{o}48'E and between 13^{o}18'N and 14^{o}15'N, and is representative for the northern Ethiopian highlands regarding its bio-physical characteristics, i.e. climate, geology, soils, topography, and land use. Ten tributaries of the Geba were monitored in this study: Suluh (SU), Genfel (GE), Agula (AG), Ilala (IL), Upper Geba (UG), May Gabat (MY), Endaselassie (EN), Middle Geba (MG), Upper Tankwa (UT) and Lower Tankwa (LT). Several of these catchments are nested. SU, GE, AG and IL are tributaries of UG. UG, MY and EN are tributaries of MG. Furthermore, UT is a tributary of LT, which flows in to Geba a few hundred meters downstream of the Middle Geba gauging station (Fig. 1).

The long term average yearly rainfall in the catchment is 646 mm, strongly concentrated in July-September. During the rainy season, convective clouds are generally formed at the end of the morning, leading to rain showers in the afternoon. The Geba catchment lies between altitudes of 936 and 3314 m.a.s.l. The topography is mountainous with plateaus that are deeply incised by river gorges. The geology of the Geba catchment consists of a basement complex plateau having an upper sedimentary rock layer with some doleritic intrusions and capped by basalt trap series. Alluvium occurs along narrow incised river valleys. The catchment is extensively cultivated including steep and stony valley sides. Effective soil and water conservation measures (stone bunds) were constructed throughout the catchment since the 1970s (Munro et al., 2008).

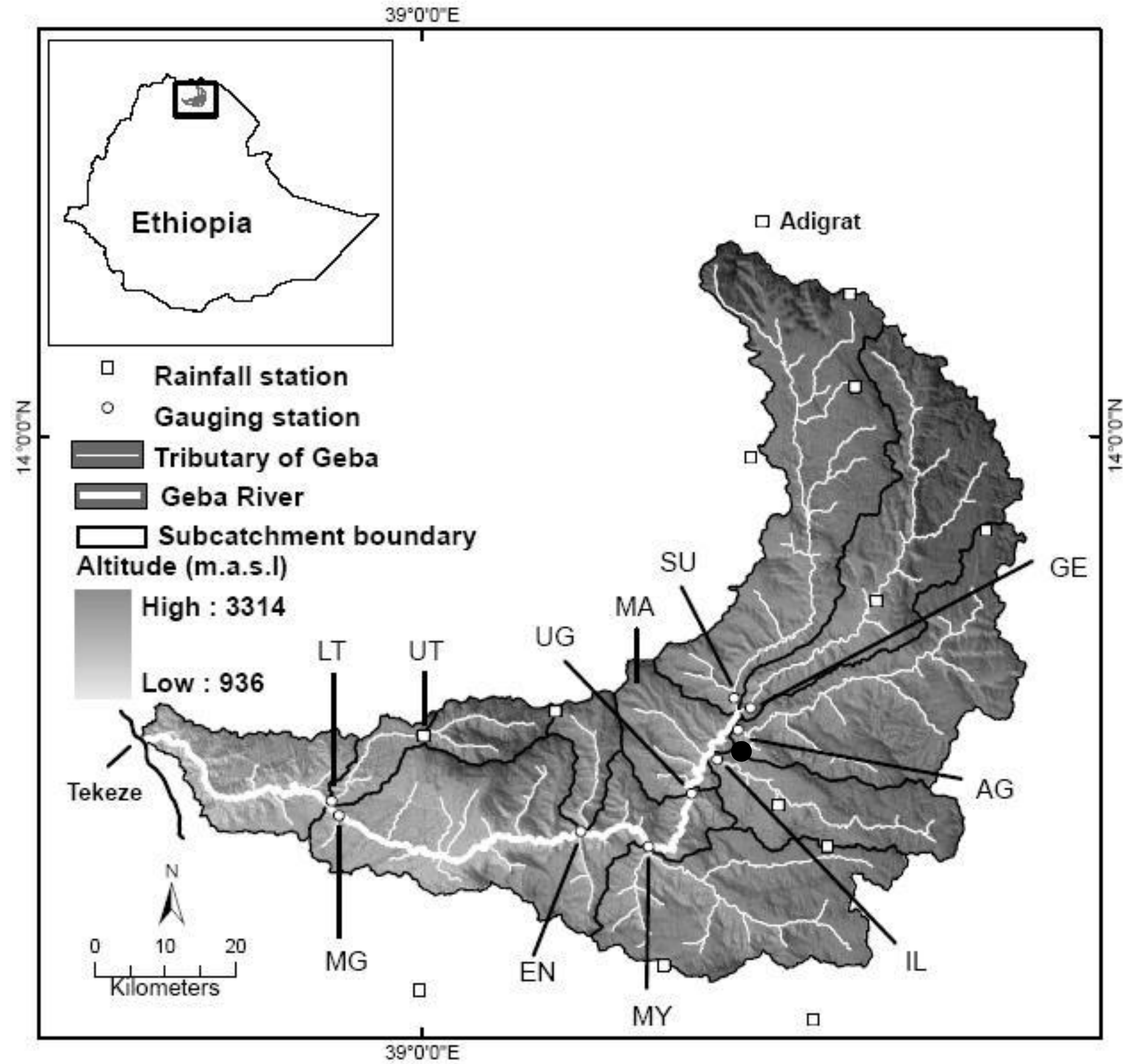

Fig. 1. River and rainfall monitoring stations of Geba catchment (after Zenebe et al., submitted). Red dot indicates excursion viewpoint.

3. Methodology

River discharge and suspended sediment concentration measurements were conducted during the rainy seasons (July – September) of 2004-2007 in ten monitoring stations of Geba catchment (Fig. 1). Discharge was determined using the velocity-area method, and depth-discharge rating curves were developed to estimate the continuous discharge from automatically recorded 10-minute interval depth series using pressure transducers (Zenebe, 2009; Vanmaercke et al., 2010). Suspended sediment samples (n = 2846) were taken at the monitoring stations in the Geba catchment from 2004 to 2007 (Vanmaercke et al., 2010). Simple and multiple regression models were applied for identifying the catchment controlling factors of river discharge and area-specific sediment yield (SSY) (Vanmaercke et al., 2010; Zenebe et al., subm.).

4. Results and discussion

4.1 River discharge

The average total estimated river discharge for the Geba catchment is 0.56 10^9 m^3 a^{-1} (Zenebe et al., subm.). It ranges between 0.013 and 0.48 10^9 m^3 a^{-1} for studied sub-catchments with a minimum area of 130 km^2 (EN) and maximum area 4592 km^2 (MG) respectively. The total runoff volumes of the sub-catchments increase with catchment area. There is a good relationship between rainfall and runoff indicating that rainfall is the major controlling factor of the river discharge.

The runoff coefficients (RCs) vary between 10% and 44% in the Geba catchment. The RCs decrease with catchment area (R^2 = 0.35) (Fig. 2); whereas the extent of limestone in the sub-catchments negatively affects runoff depth (R^2 = 0.45) and runoff coefficient (R^2 = 0.41). This is most probably due to the fractures and karstic features in the rocks.

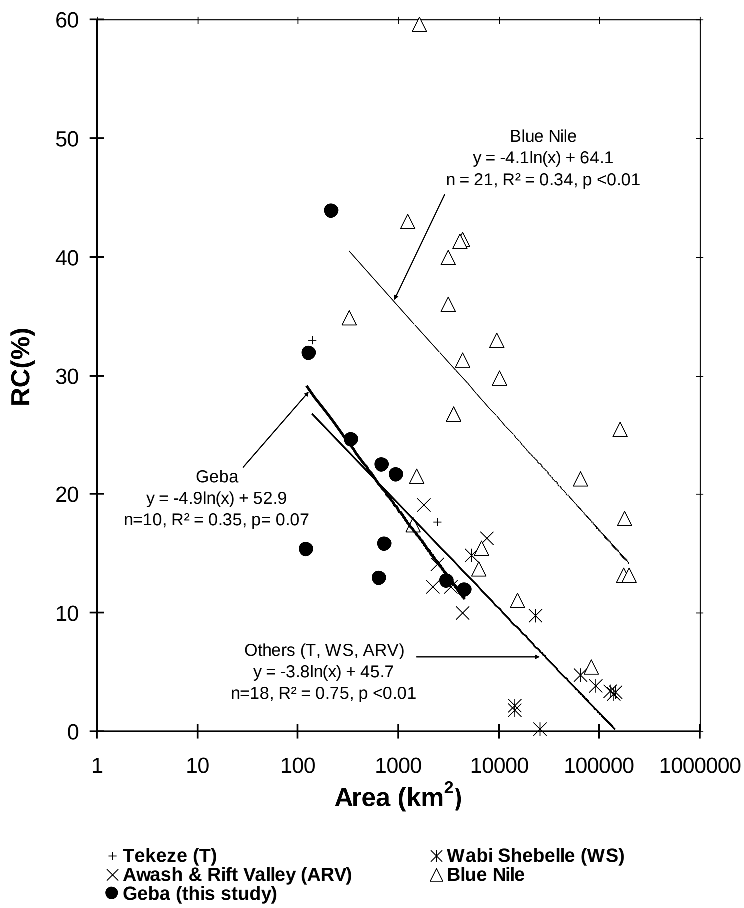

Fig.2. Annual runoff coefficients (RC) vs. drainage area (A) of Geba sub-catchments (Zenebe et al., subm) in comparison with annual RC for other Ethiopian rivers (Nyssen et al., 2004).

4.2 Suspended sediment concentration (SSC) and sediment yield

Suspended sediment concentrations (SSC) increase with runoff discharge and are significantly higher at the beginning of the rainy season than towards the end. The area-specific sediment yield (SSY) ranges between 497 and 6543 ton km^{-2} a^{-1} and varies significantly between different years and sub-catchments. There is a positive relationship between SSY and rainfall (R^2 = 0.37) indicating that rainfall is a major controlling factor of SSY (Vanmaercke et al., 2010).

4.3 Flash floods and associated sediment yield

The largest part of the runoff in all monitored catchments took place in the form of flash floods (Fig. 3), i.e. high discharge events that occur in a very short period of time. The hydrologic regime is characterized by flashfloods due to intense convective rainfall, combined with the steep topography and often poor soil cover (Vanmaercke, et al., 2010). These floods mostly occur in the evening or night and often have a steep rising limb with flow depths rising from several centimeters to 3–8 m in less than 1 h (Zenebe, 2009). With regard to sediment transport, both positive and negative hysteresis occurs in the Geba catchment. Mostly there is a positive hysteresis, which is generally attributed to sediment depletion in upper slopes of a basin, sometimes even before the runoff has peaked (Williams, 1989; Vanmaercke et al., 2010).

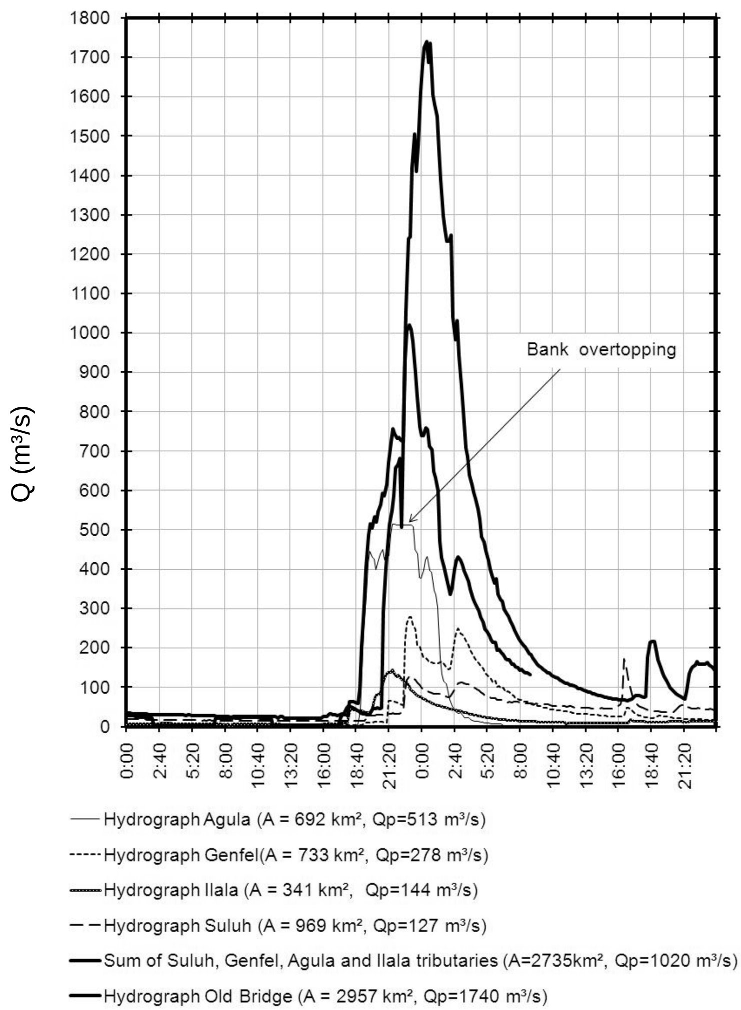

Fig. 3 Hydrograph of Upper Geba and its monitored tributaries during the flash flood of August 26-27 2006 (Zenebe et al., submitted).

4.4 SSY and catchment area

The relationship between catchment area and SSY is complex, as it is scale dependent and, furthermore, depends strongly on active erosion processes (de Vente and Poesen, 2005; Vanmaercke et al., 2010). Nyssen et al. (2004) found a decreasing significant negative relationship between A and SSY in Ethiopia. However, this relationship included almost no observations for medium-sized catchments (100–10,000 km^2), and it would underestimate the SSY values of this study. The higher than expected SSY for medium-sized catchments (Fig. 4) can probably be explained by the geomorphologic characteristics of the Ethiopian highlands (Vanmaercke et al., 2010): in catchments up to 4000 km^2 there is little possibility for redeposition as they are generally steep with well confined rivers, whereas larger catchments include extensive floodplains.

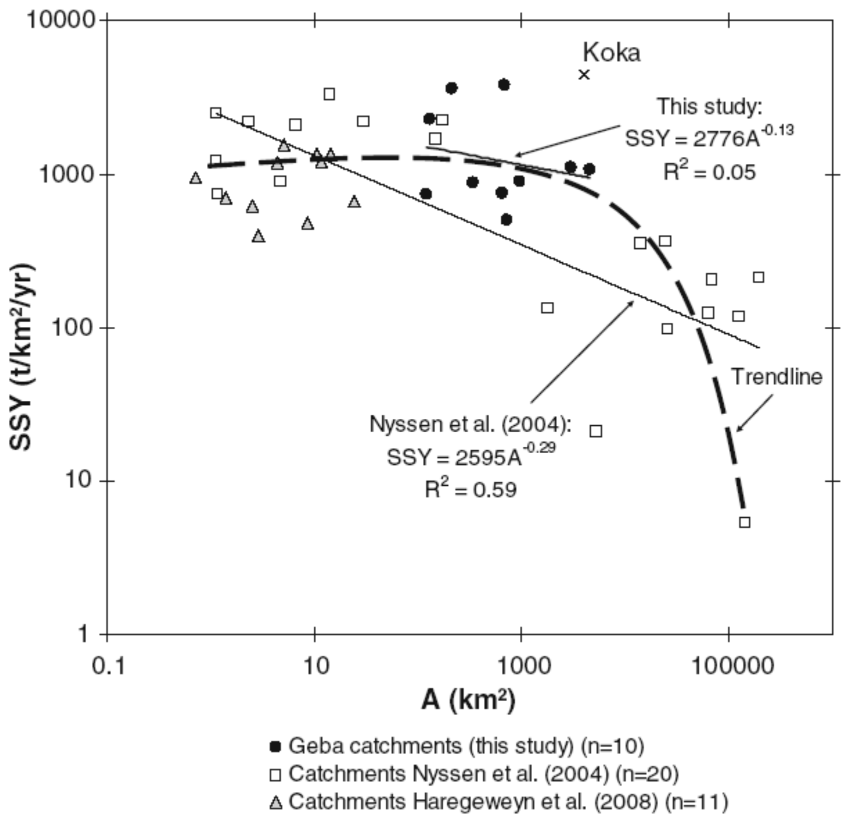

Fig. 4. Yearly sediment yield (SSY) in relation to catchment area (A). Available sediment yield data from other studies were also included (Nyssen et al., 2004; Haregeweyn et al., 2008). Data for Koka are probably overestimated and were not included in the regression analysis of Nyssen et al. (2004). Trend line is obtained by free hand curve fitting (Vanmaercke et al., 2010).

Cumulative distribution analyses of the continuous sediment export data indicate that roughly 50% of the sediment was exported during <5% of the measuring period (Fig. 5). This clearly illustrates the high temporal variability in sediment export (Vanmaercke et al., 2010). Hence, expensive measurement campaigns should focus on sampling flash floods.

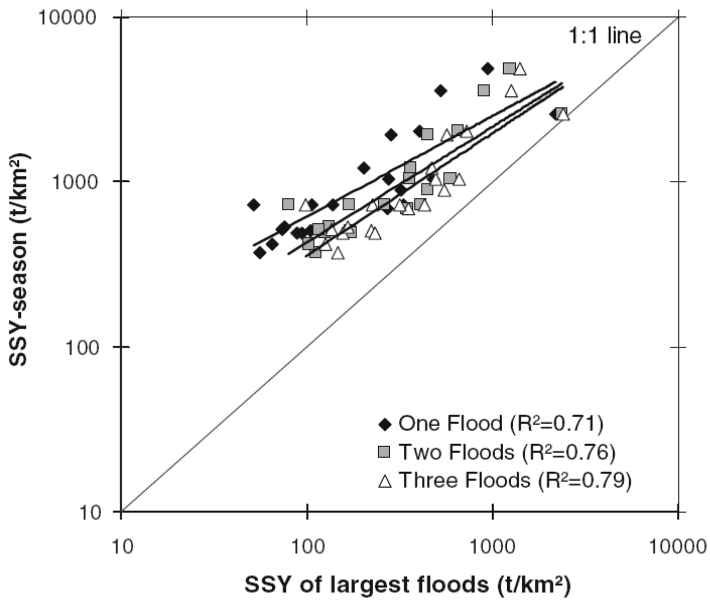

Fig. 5. Relations between the suspended sediment yield (SSY) of the largest one to three floods and the seasonal sediment yield for all data of the ten monitored sub-catchments (n=21) (Vanmaercke et al., 2010)

Soil and water conservation measures have a positive impact on the reduction of runoff and SSY of small catchments in the Ethiopian highlands (Haregeweyn et al., 2008; Nyssen et al., 2009). In contrast, this study showed no significant correlation between RC and estimated stone bund density (SBD) of each sub-catchment (Zenebe, 2009; Zenebe et al., subm.). Similar results were also found between SBD and SSY (Vanmaercke et al., 2010). Both cases (RC and SSY) tend to decrease with SBD although the relationship is insignificant. The lack of complete data on all types of soil and water conservation measures (e.g. soil bund and check dams are not considered) may result in less correlation of SBD with RC or SSY. Moreover, as stone bunds are constructed in all sub-catchments, this may result in less contrast among the catchments to generate a difference in RCs and SSY. Taking into consideration the high spatial variation in runoff and SSY, integrated watershed management would be crucial to reduce the runoff and sediment yield responses in the Geba sub-catchments.

5 Conclusions

The sub-catchments of Geba show large temporal and spatial variation in river discharge due to the variation of rainfall and other bio-physical characteristics in the catchments. Flash floods are intense with large volumes of river discharge and sediment yield causing casualties, and damage to infrastructures. Such events are difficult to predict since these floods depend mainly on local rain storms. The runoff depth is controlled by rainfall and proportion of limestone in the catchment. Runoff coefficient decreases with catchment area, as well as with the proportion of limestone in the catchment and tends to decrease with increasing density of soil conservation structures. Measured sediment yields of medium-sized catchments in the northern Ethiopian highlands are higher than estimations of previous studies. Increasing vegetation cover and strengthening on-going soil and water conservation measures have a positive effect by decreasing runoff and sediment yield. Insight of temporal and spatial variability of river discharge and sediment yield is important to prevent casualties, damage to infrastructure and allow correct design of water storage facilities.

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